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Journal of Sedimentary Petrology

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 31, NO. 2. PP. 165–188
FIGS. 1–12, JUNE, 1961

BOTTOM SEDIMENTS OF GEORGES BANK[1]

ROLAND L. WIGLEY
U. S. Fish and Wildlife Service, Bureau of Commercial Fisheries,
Biological Laboratory, Woods Hole, Massachusetts

ABSTRACT

A survey of Georges Bank bottom sediments was undertaken to provide basic data for use in studying the relationships between substrate composition and the occurrence of benthic animals, especially those which are common foods of fishes.

Particle size composition is the principal sediment character that was studied. Six statistical measures of particle size composition are given in order to designate the main features of the size-frequency distribution of each sample. These measures are: median diameter, mean diameter, coefficient of sorting, kurtosis, and two measures of skewness. In addition to these parameters, organic content, shell content, color, and textural classifications are included. In the presentation and discussion of the data, special emphasis is given to the geographic distribution of the various sediment constituents and particle size composition.

INTRODUCTION

Georges Bank is a relatively shallow portion of the New England continental shelf east of Cape Cod, Massachusetts. It has an area of approximately 12,000 square miles within the 100-fathom isobath. This is a large area, roughly equivalent to 1½ times the area of the Commonwealth of Massachusetts. Water depths between 20 and 100 fathoms occur over most of the bank, and depths over the shoals are 2 to 3 fathoms. Figure 1 is a bathymetric chart of the bank.

This bank is a submerged coastal plain cuesta (Johnson, 1925) with a steep face along the northern perimeter and a gently sloping face to the southward. The original physiography of this cuesta has been revamped by glacial action and more recently by erosion and deposition resulting from water currents.

Objectives of This Survey

Georges Bank is one of the most productive fishing grounds in the world. Hundreds of millions of pounds of fish are harvested from this bank annually and have been for decades. The kinds of fish caught are predominantly bottom-dwelling species such as cod and haddock. Commercial fishermen and biologists familiar with this area are well aware that certain species of fish inhabit only selected areas of the bank. Furthermore, it is known that many benthic invertebrate animals, which are the primary foods for many groundfish, are also selective in regard to the portions of the bank they inhabit (Wigley, 1959). Inasmuch as the composition of the bottom sediments on Georges Bank varies from place to place and the geographic distribution of some benthic invertebrates and fishes are closely associated with sediment type, a survey of Georges Bank sediments was undertaken to provide more detailed information on the geographic distribution of the various sediment types. This will provide a basis for future studies concerning the significance of sediments as they affect the occurrence of bottom-dwelling animals.

Specific objectives of this survey were twofold: (1) to ascertain the particle size composition and related components of the sediments, and (2) to make a preliminary quantitative study of the benthic fauna. Only the sediments will be discussed in this report.

Previous Studies

The first observations of Georges Bank sediments were made by the U. S. Coast Survey (Pourtalès, 1869) and the U. S. Fish Commission (Murray, 1885). These findings have been supplemented from time to time and are recorded on standard navigational charts published by the U. S. Coast and

[1] Manuscript received April 11, 1960.

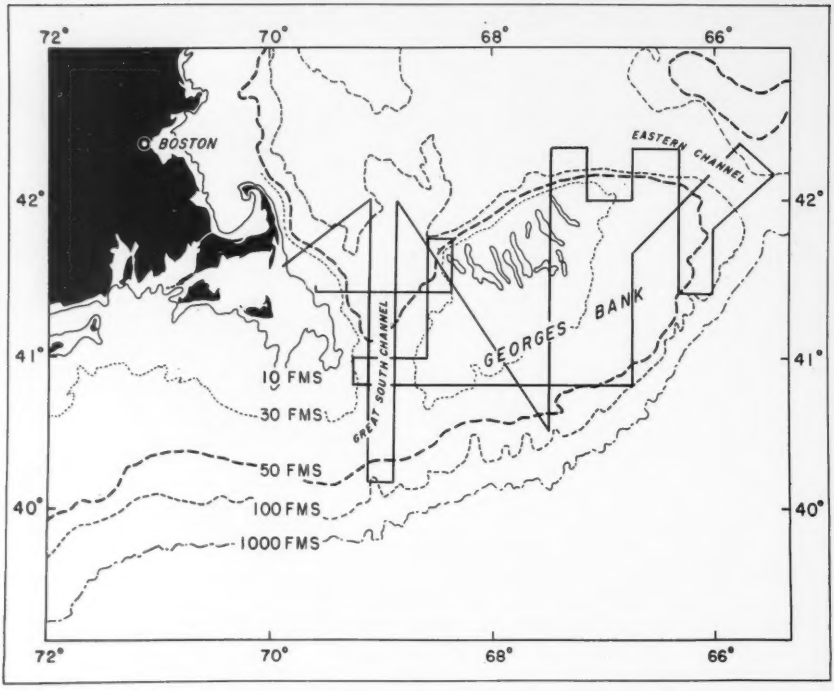

FIG. 1.—Bathymetric chart of Georges Bank with track of sampling stations plotted.

Geodetic Survey. The sediment data plotted on these charts is necessarily inconspicuous. Consequently, for purposes of analysis and study, these charts were reproduced in a more comprehensible format by Shepard (1932). Shepard, Trefethen, and Cohee (1934) refined this sediment chart by incorporating with the old survey data some additional information from various sources. Five years later another revision was published by Shepard (1939). Most of these data, as explained by Shepard (1939), are rather cursory observations of small sediment samples taken by means of sounding leads and small snapper-type samplers. Nevertheless, a check on several hundred samples by Shepard and Cohee (1936) has confirmed the general reliability of these descriptions.

A fairly recent sediment study, using an entirely new set of samples, was conducted by Stetson (1938). His work was based on numerous samples from 13 transects across the continental shelf on the eastern coast of the United States between Maine and Florida. However, only a small section of the area studied by Stetson, a coastal strip east of Cape Cod, coincides with the area included in the present investigation. In this sector he found four sediment zones approximately parallel to the coastline. They occurred in the following order, proceeding seaward from shore: (a) well sorted fine sand, (b) well sorted coarse sand, (c) poorly sorted silt and clay, and (d) well sorted sand.

The U. S. Coast and Geodetic Survey, in collaboration with the Woods Hole Oceanographic Institution, prepared a bottom sediment chart of the Georges Bank region. This chart, U.S.C. & G.S. No. 1107-BS, dated August 1942, was compiled for the National

Defense Research Committee and appears to be based largely on U. S. Coast and Geodetic Survey results, discussed above, and possibly supplemented by other samples.

A special sediment chart of Georges Bank and vicinity was prepared by Colton (1955) for use in connection with a study of the distribution of haddock. For this purpose, sediments were classified into two categories: (1) particle diameters greater than 0.1 mm, and (2) particle diameters mostly less than 0.1 mm. This chart is based on sediment data from U. S. Coast and Geodetic Survey charts 1106A and 1107A, supplemented by more than 250 new bottom samples.

METHODS AND MATERIALS

The samples were collected August 20–30, 1957, aboard the U. S. Fish and Wildlife Service research vessel *Albatross III* at 223 locations spaced at 5-mile intervals along the track shown in figure 1. Most of the traverses cross the bank perpendicular to the depth gradient, and a large proportion of the samples were taken from the bank's perimeter where the sediments were more varied. Sediment samples were collected with a Smith-McIntyre sampler (Smith and McIntyre, 1954). This sampler was selected because of its moderately large capacity, 1/10 m^2, and its reliability in securing a sample under difficult conditions. A secondary factor considered in selecting this sampler was the desirability of obtaining quantitative faunal samples at the same time sediments were collected.

Sediment from the sampler was emptied into a tub. Macroscopic organisms were removed and a 1-quart subsample packed in a cardboard container. Ashore the samples were partially air-dried and sent to the New York Soil Testing Laboratory for analysis.

Mechanical analysis of the sediments was conducted, with slight modification, according to the procedure outlined by Richards (1954). In brief, the analysis was as follows: The sample was air-dried, mixed, and quartered. One quarter was sorted through a graded series of sieving screens with mesh openings of 16, 8, 4, and 2 mm. Material remaining on each screen was weighed and recorded. The mollusk shell fragments in all of these fractions were separated from the inorganic matter and weighed.

A 10-gm sample of sediment composed of fractions less than 2 mm in diameter was treated with hydrogen peroxide to remove the organic matter. This portion of the sample was then water-washed and later oven-dried at 110° C and weighed. A solution of sodium hexametaphosphate was added to the sample, and it was placed in a reciprocating shaker overnight for dispersion. The sample was then washed through a 0.062 mm sieve to separate silts and clays from the sand fractions. After drying, the sands were sorted through a graded series of sieves having mesh openings of 1.0, 0.5, 0.25, and 0.125 mm by agitation in a mechanical shaker for 3 minutes. The weight of each fraction was measured and recorded.

Standard pipetting methods were used in determining the amounts of silt (0.062 -0.004 mm) and clay (<0.004 mm).

Organic content was determined from a portion of the sample not utilized in the particle size analysis. A 2-gm sample composed of particles less than 1 mm in size was subjected to wet combustion of the organic matter using chromic and sulfuric acids according to the modified Walkley procedure described by Peech and others (1947).

Color was determined by comparing the dry sample with Munsell Soil Color Chart.[2]

The six parameters outlined by Inman (1952) for describing the size distribution of sediment components were calculated for each of the samples considered in this study. These parameters: the mean diameter, median diameter, standard deviation, kurtosis, and two measures of skewness, provide data necessary for recalculation of sediment cumulative frequency curves, thus eliminating the need for reporting the complete mechanical analyses. Values for all descriptive measures for each sediment are tabulated either in the text or the appendix. Formulae for all measures used herein may be found in Inman's paper.

In order to facilitate the mathematical computations and comparisons of the various descriptive parameters, the phi (ϕ) notation of Krumbein (1936) is used. Phi, as utilized in this analysis, is the symbol for

[2] Munsell Soil Color Charts, 1954 edition. Munsell Color Company, Inc., 10 East Franklin Street, Baltimore 2, Maryland.

TABLE 1.—*Textural grades and Wentworth classes with corresponding size ranges of each in millimeters and phi units*

Wentworth classes	Grade	Size (mm)	Phi units (ϕ)
	Gravel	32	−5
Coarse pebble		16	−4
Medium pebble		8	−3
Small pebble		4	−2
Granule		2	−1
Very coarse sand	Sand	1	0
Coarse sand		0.5	1
Medium sand		0.25	2
Fine sand		0.125	3
Very fine sand		0.062	4
Silt	Silt	0.004	8
Clay	Clay	<0.004	>8

the negative logarithm to the base 2 of particle diameter in millimeters. A conversion table from millimeters to phi units is included in table 1.

In presenting the data in graphic form, especially in regard to geographic distribution (figs. 1, 2, and 3), it has been necessary in many instances to extrapolate a considerable distance. It should be mentioned that in doing this, previously published data have been used for guidance.

RESULTS

General

The results of this study are in basic agreement with previous investigations outlined above, but many refinements are made and a considerable amount of new information is added. Sediments on Georges Bank and adjacent areas sampled consist chiefly of sands. A large section in the central part of the bank is composed primarily of medium sand—particle diameters between 0.50 and 0.25 mm. A rather broad strip in the southwestern section of the bank and a narrow band along most of the

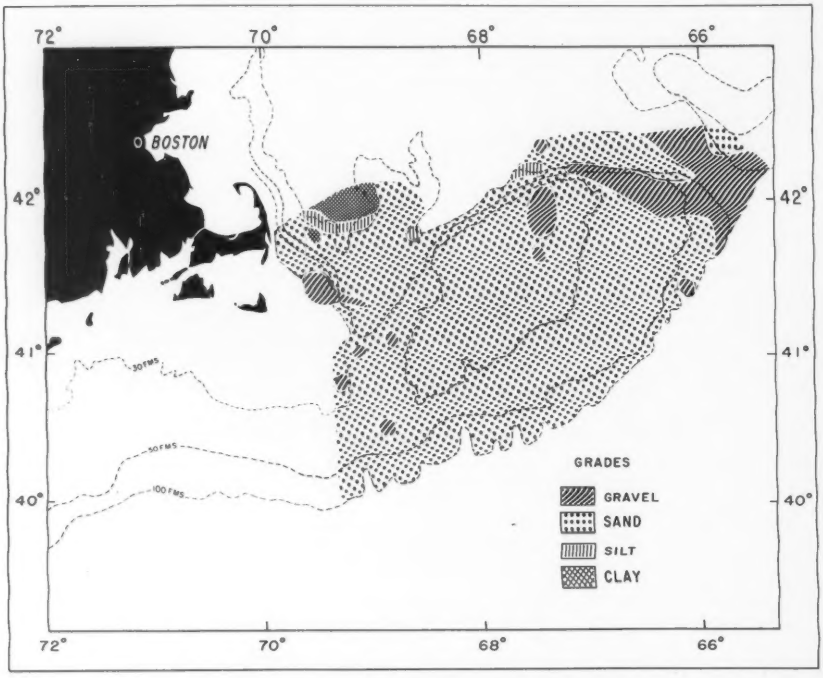

FIG. 2.—Geographic distribution of sediment grades.

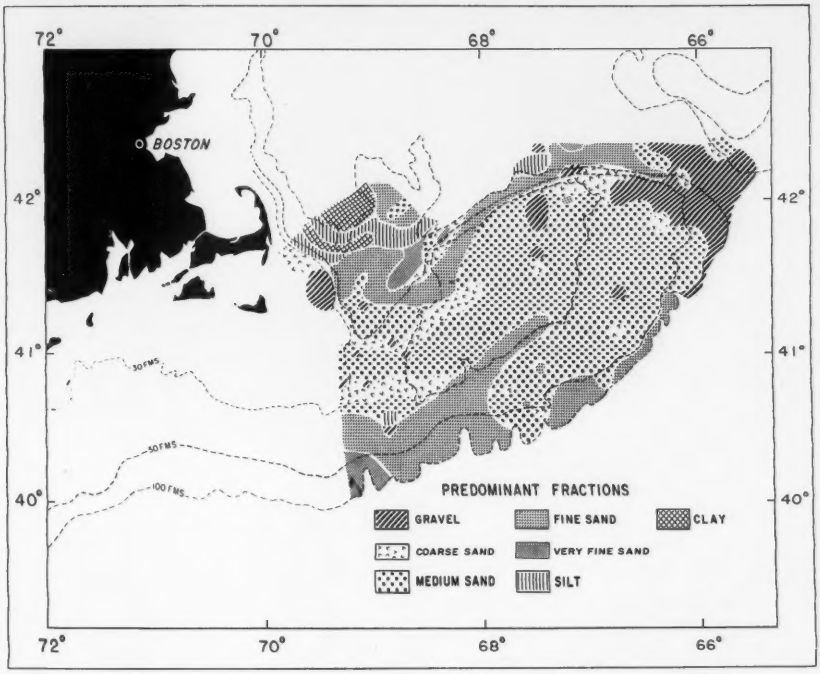

FIG. 3.—Geographic distribution of sediment predominant fractions.

bank's periphery consists mainly of fine sand—0.25 to 0.125 mm. Very fine sands, silts, and clays surround the bank in the deeper water except on the eastern end where gravels predominate.

Table 2 contains the main body of data resulting from this study. Supplementary data which may be used for reference, such as station location, median and mean particle diameter, two measures of size distribution skewness, and kurtosis are listed in the appendix.

Sediment Types

Some of the most useful information resulting from this survey is the delineation of the areal distribution of the various sediment types. Sediments can be classified according to several systems, depending upon the degree of refinement desired. In this report three classifications of sediment type have been selected: (1) grades (2) predominant fractions, and (3) textural classes.

Grades—The first classification of sediment types to be discussed, and the least refined, is a series of only four categories designated as grades. The four grades are: gravel, sand, silt, and clay. Grade designation for each sample is determined by that fraction most abundant in the sample. Size range and name of each grade are included in table 1. The grade of each sample is listed in column 3 of table 2, and the geographic distribution of these grades is illustrated in figure 2.

It is evident from figure 2 that sand is by far the most prevalent grade in this region, comprising more than three-fourths of the entire area. Sand also occurs in the deep water adjacent to the northeastern edge of the bank and is present on the eastern side of the Eastern Channel. Relatively small tracts of silt and clay occur in the deep water area northwest of Georges Bank.

TABLE 2.—*Principal descriptive features of each sediment sample and the water depth at the locality from which they were taken*

Station[1]	Water depth (fms)	Grade	Predominant fraction	Textural class	Median diameter (mm)	Phi deviation measure (φ)	Organic content (%)	Shell content (%)	Color
1	15	Sand	Coarse sand	Sand	1.07	0.85	0.1	<1	V. pale brown (S)[2]
2	44	Sand	Coarse sand	Sand	0.90	2.05	0.4	6	Gray brown
3	81	Sand	Silt	Silty sand	0.07	1.75	1.2	0	Lt. brown gray
4	95	Clay	Clay	Silty clay	0.02	1.95	1.2	0	Gray
5	106	Silt	Silt	Clayey silt	0.02	1.80	2.6	0	Gray
6	111	Clay	Clay	Silty clay	0.01	1.15	3.0	0	Gray
7	114	Clay	Clay	Silty clay	0.01	0.90	3.4	0	Gray
8	122	Clay	Clay	Silty clay	0.01	1.15	3.4	0	Gray
9	107	Clay	Clay	Sand-silt-clay	0.04	3.10	2.2	0	Gray
10	106	Clay	Clay	Silty clay	0.02	1.75	3.2	0	Lt. gray brown
11	98	Silt	Silt	Clayey silt	0.02	1.80	2.7	0	Lt. gray brown
12	96	Sand	Clay	Sand-silt-clay	0.06	3.15	1.5	0	Lt. gray brown
13	87	Sand	Fine sand	Sand	0.33	2.15	0.6	0	Lt. gray brown
14	90	Sand	Fine sand	Gravelly sand	0.44	3.15	0.6	0	Gray
15	79	Sand	Medium sand	Sand	0.50	0.80	0.4	0	Lt. brown gray
16	86	Sand	Medium sand	Gravelly sand	1.15	2.55	0.4	<1	Lt. brown gray
17	90	Gravel	Gravel	Sandy gravel	4.20	2.75	0.3	1	Lt. brown gray
18	83	Sand	Medium sand	Gravelly sand	0.66	2.15	0.6	<1	Gray brown
19	66	Sand	Medium sand	Gravelly sand	1.25	1.95	<0.1	2	Pale brown (S)
20	45	Sand	Coarse sand	Sand	0.72	0.35	0.1	<1	V. pale brown (S)
21	42	Sand	Medium sand	Gravelly sand	0.54	2.10	0.1	<1	Lt. yellowish brown (S)
22	41	Sand	Medium sand	Gravelly sand	2.30	2.85	0.1	1	Lt. brown gray (S)
23	37	Gravel	Gravel	Sandy gravel	5.65	2.95	0.2	1	Gray brown (S)
24	42	Sand	Coarse sand	Gravelly sand	1.07	1.70	<0.1	4	Pale brown (S)
25	40	Sand	Medium sand	Sand	0.62	1.90	0.1	1	V. pale brown (S)
26	38	Sand	Fine sand	Sand	0.36	0.50	0.2	<1	V. pale brown (S)
27	43	Sand	Fine sand	Sand	0.19	0.15	0.6	0	Gray brown
28	46	Sand	Fine sand	Sand	0.18	0.40	0.7	0	Lt. brown gray
29	48	Sand	Very fine sand	Sand	0.16	0.50	0.7	0	Gray brown
30	52	Sand	Very fine sand	Sand	0.15	0.55	0.6	1	Gray brown
31	58	Sand	Very fine sand	Sand	0.22	1.60	0.6	3	Gray brown
32	74	Sand	Very fine sand	Sand	0.17	1.20	0.6	1	Gray brown
33	83	Sand	Fine sand	Sand	0.24	0.65	0.6	0	Lt. brown gray
34	60	Sand	Fine sand	Sand	0.29	1.05	0.4	1	Lt. brown gray
35	49	Sand	Fine sand	Sand	0.27	0.90	0.4	4	Lt. gray brown
36	44	Sand	Fine sand	Sand	0.21	0.30	0.4	1	Lt. brown gray
37	39	Gravel	Gravel	Gravel	22.75	0.00	0.1	8	Light gray (S)
38	37	Sand	Silt	Silty sand	0.22	1.95	0.2	4	Light gray (S)
39	34	Sand	Medium sand	Sand	0.66	1.90	0.1	<1	V. pale brown (S)
40	33	Sand	Medium sand	Sand	0.72	1.90	0.1	2	V. pale brown (S)
41	35	Sand	Medium sand	Gravelly sand	0.54	2.55	0.1	<1	V. pale brown (S)
42	37	Sand	Medium sand	Sand	0.66	0.45	0.2	0	V. pale brown (S)
43	34	Sand	Medium sand	Sand	0.72	1.10	0.1	0	V. pale brown (S)
44	35	Gravel	Gravel	Gravel	11.40	1.05	<0.1	2	Pale brown (S)
45	45	Sand	Medium sand	Sand	0.41	1.30	0.2	8	Lt. brown gray (S)
46	51	Sand	Medium sand	Sand	0.44	1.60	0.1	<1	Lt. brown gray (S)
47	61	Sand	Fine sand	Sand	0.29	1.15	0.3	8	Lt. olive brown (S)
48	73	Sand	Fine sand	Sand	0.22	0.50	0.5	<1	Gray brown
49	80	Sand	Very fine sand	Sand	0.17	1.45	<0.1	0	Gray brown
50	85	Sand	Very fine sand	Silty sand	0.11	1.40	1.0	0	Gray brown
51	82	Sand	Fine sand	Gravelly sand	0.19	2.70	0.9	0	Gray brown
52	90	Sand	Silt	Sand-silt-clay	0.08	3.25	1.8	<1	Lt. olive gray
53	87	Sand	Silt	Sand-silt-clay	0.25	3.65	1.7	0	Gray brown
54	74	Sand	Medium sand	Sand	0.66	1.35	0.7	0	Olive gray
55	76	Sand	Fine sand	Sand	0.41	1.60	0.6	0	Gray brown
56	84	Sand	Medium sand	Gravelly sand	0.66	2.70	0.8	0	Gray brown
57	84	Sand	Fine sand	Silty sand	0.25	2.85	1.3	0	Lt. brown gray
58	92	Silt	Silt	Clayey silt	0.12	0.65	3.3	0	Lt. olive gray
59	99	Sand	Very fine sand	Silty sand	0.08	1.25	1.9	0	Lt. olive gray
60	93	Sand	Medium sand	Sand	0.38	2.20	0.9	0	Gray brown
61	27	Sand	Coarse sand	Gravelly sand	0.82	1.85	0.1	<1	Pale olive (S)
62	25	Sand	Fine sand	Sand	0.46	2.25	0.2	<1	Pale yellow (S)
63	26	Sand	Fine sand	Sand	0.36	0.20	0.3	<1	Light gray (S)
64	24	Sand	Coarse sand	Sand	1.00	0.45	<0.1	0	V. pale brown (S)
65	17	Sand	Coarse sand	Sand	1.32	0.25	<0.1	<1	V. pale brown (S)
66	16	Sand	Medium sand	Sand	0.54	0.55	0.1	<1	White (S)
67	23	Sand	Medium sand	Sand	0.66	0.40	0.1	<1	Light gray (S)
68	24	Sand	Medium sand	Sand	0.36	0.10	0.1	<1	White (S)
69	27	Sand	Fine sand	Sand	0.27	0.30	0.2	2	White (S)
70	28	Sand	Fine sand	Sand	0.25	0.30	0.2	0	Light gray (S)
71	33	Sand	Medium sand	Sand	0.58	0.85	0.2	0	Pale yellow (S)
72	36	Sand	Medium sand	Sand	0.50	0.55	0.2	2	Lt. yellowish brown (S)
73	38	Sand	Medium sand	Sand	0.50	0.75	0.2	8	Lt. yellowish brown (S)
74	44	Sand	Fine sand	Sand	0.24	0.85	0.4	3	Pale olive
75	51	Sand	Medium sand	Sand	0.50	0.55	0.2	2	Pale yellow (S)
76	66	Sand	Medium sand	Sand	0.50	0.95	0.2	2	Pale yellow (S)
78	64	Sand	Medium sand	Sand	0.38	0.80	0.2	1	Pale yellow (S)

[1] Station is synonymus with sample number.
[2] (S) is an abbreviation for speckled, V.—Very, Lt.—Light, and Dk.—Dark.

TABLE 2.—*Continued*

Station[1]	Water depth (fms)	Grade	Predominant fraction	Textural class	Median diameter (mm)	Phi deviation measure (ϕ)	Organic content (%)	Shell content (%)	Color
79	47	Sand	Coarse sand	Sand	0.82	0.65	0.2	1	Lt. yellowish brown (S)
80	46	Sand	Medium sand	Sand	0.38	0.85	0.2	8	Pale olive (S)
81	44	Sand	Medium sand	Sand	0.38	0.80	0.2	8	Pale yellow (S)
82	42	Sand	Fine sand	Sand	0.31	0.65	0.4	11	Pale yellow (S)
83	37	Sand	Medium sand	Sand	0.36	0.55	0.2	6	Pale yellow (S)
84	33	Sand	Medium sand	Sand	0.38	0.55	0.2	0	Pale yellow (S)
85	30	Sand	Fine sand	Sand	0.27	0.40	0.2	0	Light gray (S)
86	24	Sand	Fine sand	Sand	0.36	0.35	0.2	1	White (S)
87	16	Sand	Medium sand	Sand	0.72	0.80	0.2	5	White (S)
88	18	Sand	Medium sand	Sand	0.46	0.50	0.2	2	Pale yellow (S)
89	27	Sand	Medium sand	Sand	0.50	0.45	0.1	1	Pale yellow (S)
90	23	Sand	Coarse sand	Sand	0.82	0.80	0.2	1	Pale yellow (S)
91	27	Gravel	Gravel	Sandy gravel	18.50	2.70	<0.1	6	Light gray (S)
92	18	Sand	Medium sand	Gravelly sand	1.42	2.00	0.1	2	Light gray (S)
93	29	Gravel	Gravel	Gravel	13.00	2.35	<0.1	1	Pale olive (S)
94	25	Gravel	Gravel	Sandy gravel	5.25	2.40	0.1	<1	Pale yellow (S)
95	25	Gravel	Gravel	Sandy gravel	10.50	2.50	<0.1	1	Pale yellow (S)
96	44	Sand	Medium sand	Sand	0.66	1.90	0.1	6	Pale yellow (S)
97	85	Sand	Fine sand	Sand	0.21	0.75	0.9	0	Olive gray
98	126	Silt	Silt	Sandy silt	0.07	1.65	2.3	0	Olive gray
99	151	Sand	Fine sand	Sand	0.27	2.25	0.9	0	Gray brown
100	158	Gravel	Gravel	Sandy gravel	13.00	3.20	0.3	0	Lt. brown gray
101	144	Sand	Fine sand	Gravelly sand	0.31	2.85	0.5	0	Lt. olive gray
102	128	Sand	Very fine sand	Silty sand	0.18	2.45	0.8	0	Lt. olive gray
103	92	Sand	Fine sand	Sand	0.25	0.50	0.3	0	Lt. olive gray (S)
104	34	Gravel	Gravel	Sandy gravel	15.00	2.65	0.1	17	Lt. olive gray (S)
105	32	Sand	Coarse sand	Sand	1.32	1.10	<0.1	5	Light gray (S)
106	26	Sand	Coarse sand	Gravelly sand	2.00	1.70	<0.1	<1	Light gray (S)
107	30	Sand	Fine sand	Sand	0.18	0.05	0.1	0	Olive (S)
108	32	Sand	Medium sand	Sand	0.46	0.20	<0.1	0	White (S)
109	35	Sand	Medium sand	Sand	0.66	0.20	<0.1	0	Light gray (S)
110	40	Sand	Coarse sand	Sand	0.90	0.45	<0.1	9	White (S)
111	40	Sand	Medium sand	Gravelly sand	1.75	2.00	<0.1	2	Light gray (S)
112	39	Gravel	Gravel	Gravel	13.00	2.30	<0.1	1	Pale brown (S)
113	39	Gravel	Gravel	Gravel	22.75	0.00	<0.1	7	——
114	88	Sand	Coarse sand	Sand	0.75	1.05	<0.1	1	V. pale brown (S)
115	152	Sand	Fine sand	Sand	0.19	1.30	0.5	0	Lt. olive gray
116	182	Sand	Fine sand	Gravelly sand	0.33	2.40	0.5	0	Gray brown
117	191	Sand	Fine sand	Sand	0.29	1.65	0.3	0	Gray brown
118	172	Sand	Medium sand	Gravelly sand	1.75	3.05	0.1	0	Olive gray
119	156	Gravel	Gravel	Sandy gravel	4.27	2.85	0.1	0	Olive gray (S)
120	141	Gravel	Gravel	Gravel	22.75	1.15	<0.1	0	Gray brown (S)
121	121	Sand	Medium sand	Gravelly sand	0.72	2.30	0.1	0	Lt. brown gray (S)
122	105	Sand	Fine sand	Gravelly sand	0.62	2.20	<0.1	0	Gray brown (S)
123	58	Sand	Gravel	Gravelly sand	1.24	2.70	<0.1	2	Light gray (S)
124	47	Gravel	Gravel	Gravel	8.00	2.10	<0.1	1	Light gray (S)
125	46	Gravel	Gravel	Gravel	22.75	1.55	0.1	9	Light gray (S)
126	44	Gravel	Gravel	Gravel	9.20	2.00	0.1	3	Light gray (S)
127	43	Sand	Coarse sand	Sand	0.94	1.15	<0.1	15	Lt. brown gray (S)
128	43	Sand	Medium sand	Sand	0.62	0.40	<0.1	2	V. pale brown (S)
129	47	Sand	Medium sand	Sand	0.66	0.75	0.1	14	V. pale brown (S)
130	48	Sand	Medium sand	Sand	0.72	0.65	0.2	10	Pale brown (S)
131	50	Sand	Medium sand	Sand	0.90	1.70	0.1	5	Light gray (S)
132	61	Sand	Medium sand	Sand	0.72	1.65	<0.1	9	Light gray (S)
133	67	Sand	Fine sand	Sand	0.31	0.90	<0.1	8	Light gray (S)
134	76	Gravel	Gravel	Sandy gravel	3.00	2.85	0.1	3	Lt. brown gray (S)
135	130	Sand	Gravel	Gravelly sand	2.45	2.05	<0.1	<1	Light gray (S)
136	79	Sand	Medium sand	Gravelly sand	0.94	1.75	0.2	1	Lt. brown gray (S)
137	58	Sand	Medium sand	Sand	0.66	0.60	<0.1	1	Light gray (S)
138	52	Sand	Medium sand	Gravelly sand	0.90	1.40	<0.1	8	Lt. brown gray (S)
139	54	Sand	Medium sand	Sand	0.66	0.40	0.1	2	Light gray (S)
140	50	Sand	Gravel	Gravelly sand	1.62	1.65	<0.1	6	Pale brown (S)
141	59	Gravel	Gravel	Sandy gravel	4.57	2.50	<0.1	2	Lt. brown gray (S)
142	102	Gravel	Gravel	Gravel	22.75	1.00	<0.1	0	Lt. brown gray (S)
144	134	Gravel	Gravel	Gravel	22.75	0.40	<0.1	<1	——
146	75	Gravel	Gravel	Sandy gravel	8.00	2.40	<0.1	<1	Lt. brown gray (S)
148	60	Gravel	Gravel	Gravel	18.50	2.40	<0.1	3	Lt. brown gray (S)
149	76	Sand	Medium sand	Gravelly sand	0.72	3.00	0.1	3	Lt. brown gray (S)
150	83	Sand	Medium sand	Gravelly sand	0.90	1.80	0.1	<1	Lt. brown gray (S)
151	126	Sand	Coarse sand	Gravelly sand	1.75	1.45	0.1	0	Gray brown (S)
152	130	Gravel	Gravel	Sandy gravel	3.72	1.95	<0.1	0	Gray brown (S)
153	129	Gravel	Gravel	Gravel	22.75	0.00	<0.1	0	——
154	110	Sand	Coarse sand	Sand	0.72	0.30	0.1	<1	Light gray (S)
156	44	Gravel	Gravel	Gravel	11.40	1.45	<0.1	<1	Brown (S)
157	43	Gravel	Gravel	Gravel	18.50	1.05	0.1	3	Pale yellow (S)
158	45	Sank	Medium sand	Gravelly sand	2.00	2.30	0.1	10	Light gray (S)
159	43	Sand	Medium sand	Sand	0.66	0.65	0.1	14	V. pale brown (S)
160	40	Sand	Medium sand	Gravelly sand	1.54	2.90	<0.1	18	White (S)
161	36	Sand	Medium sand	Sand	0.66	1.15	0.1	7	White (S)
162	38	Sand	Medium sand	Sand	0.38	0.50	0.1	2	Light gray (S)

(*Table 2 continud on following page*)

TABLE 2.—*Continued*

Station[1]	Water depth (fms)	Grade	Predominant fraction	Textural class	Median diameter (mm)	Phi deviation measure (ϕ)	Organic content (%)	Shell content (%)	Color
163	39	Sand	Medium sand	Sand	0.41	0.50	0.1	4	Light gray (S)
164	38	Sand	Medium sand	Sand	0.44	0.35	0.1	0	Light gray (S)
165	43	Sand	Gravel	Gravelly sand	1.24	3.05	0.1	9	Light gray (S)
166	42	Sand	Medium sand	Sand	0.72	0.55	0.1	<1	V. pale brown (S)
167	44	Sand	Medium sand	Sand	0.54	0.45	0.1	12	Light gray (S)
168	42	Sand	Coarse sand	Sand	0.76	0.60	0.1	6	V. pale brown (S)
169	47	Sand	Medium sand	Sand	0.62	0.50	0.1	3	Light gray (S)
170	49	Sand	Medium sand	Sand	0.38	0.35	0.2	17	Pale olive (S)
171	56	Sand	Fine sand	Sand	0.36	0.40	0.2	25	Pale olive (S)
172	133	Sand	Fine sand	Sand	0.21	0.60	0.5	0	Lt. olive gray (S)
173	62	Sand	Medium sand	Sand	0.58	0.55	0.1	7	Light gray (S)
174	56	Sand	Fine sand	Sand	0.28	0.45	0.3	9	Pale olive (S)
175	52	Sand	Fine sand	Sand	0.31	0.55	0.2	4	Pale olive (S)
176	52	Sand	Fine sand	Sand	0.25	0.50	0.4	2	Lt. olive gray (S)
177	50	Sand	Fine sand	Sand	0.22	0.70	p.3	16	Pale olive (S)
178	46	Sand	Medium sand	Sand	0.36	0.80	0.3	7	Pale olive (S)
179	44	Sand	Medium sand	Sand	0.36	0.85	0.2	13	Lt. olive gray (S)
180	41	Sand	Medium sand	Sand	0.66	0.70	0.2	0	Pale olive (S)
181	37	Sand	Coarse sand	Sand	0.94	1.20	0.1	2	V. pale brown (S)
182	38	Sand	Medium sand	Sand	0.41	0.45	0.1	0	Pale yellow (S)
183	38	Sand	Fine sand	Sand	0.29	0.45	0.3	0	Pale olive (S)
184	36	Sand	Fine sand	Sand	0.29	0.55	0.2	<1	Pale yellow (S)
185	32	Sand	Fine sand	Sand	0.27	0.25	0.2	<1	Light gray (S)
186	31	Sand	Fine sand	Sand	0.33	0.30	0.1	2	White (S)
187	25	Sand	Coarse sand	Sand	0.80	0.40	0.4	0	Light gray (S)
188	29	Sank	Medium sand	Sand	0.50	0.50	0.1	<1	Light gray (S)
189	34	Sand	Coarse sand	Gravelly sand	1.15	1.55	0.1	1	Light gray (S)
190	36	Sand	Coarse sand	Sand	0.72	0.90	0.1	0	V. pale brown (S)
191	36	Sand	Medium sand	Gravelly sand	0.62	2.40	0.1	<1	Light gray (S)
192	42	Sand	Medium sand	Sand	0.46	0.60	0.2	15	Light gray (S)
193	36	Sand	Coarse sand	Sand	1.00	0.80	0.1	1	Light gray (S)
194	34	Sand	Medium sand	Gravelly sand	1.00	2.10	<0.1	6	Light gray (S)
195	28	Gravel	Gravel	Sandy gravel	18.50	2.45	<0.1	1	Light gray (S)
196	35	Sand	Medium sand	Gravelly sand	0.62	2.45	0.1	1	Light gray (S)
197	37	Sand	Medium sand	Gravelly sand	1.32	2.55	0.1	4	Lt. brown gray (S)
198	33	Sand	Medium sand	Gravelly sand	1.32	2.10	0.2	2	Gray brown
199	36	Gravel	Gravel	Sandy gravel	12.25	2.90	0.1	8	Gray brown
200	43	Sand	Medium sand	Gravelly sand	0.82	2.20	0.1	1	Lt. brown gray
201	42	Sand	Medium sand	Gravelly sand	1.32	2.50	0.1	<1	Lt. brown gray
202	36	Sand	Coarse sand	Sand	0.82	0.75	0.1	<1	Pale yellow
203	35	Gravel	Gravel	Sandy gravel	5.65	2.25	<0.1	<1	Lt. brown gray
204	25	Sand	Medium sand	Gravelly sand	1.32	1.85	<0.1	2	Lt. yellowish brown
205	31	Sand	Medium sand	Gravelly sand	1.00	2.35	0.1	<1	Lt. yellowish brown
206	31	Sand	Coarse sand	Gravelly sand	1.50	1.90	<0.1	<1	Lt. brown gray
207	34	Sand	Medium sand	Gravelly sand	0.44	2.20	0.1	0	Lt. brown gray
208	37	Sand	Fine sand	Sand	0.21	0.60	0.8	0	Gray brown
209	47	Sand	Fine sand	Sand	0.18	0.55	0.6	<1	Lt. olive brown
210	56	Sand	Coarse sand	Sand	0.66	1.70	2.5	2	Lt. yellowish brown
211	72	Sand	Very fine sand	Gravelly sand	0.58	2.85	1.0	0	Gray brown
213	102	Sand	Very fine sand	Clayey sand	0.24	2.20	1.3	0	Gray brown
214	105	Sand	Medium sand	Gravelly sand	0.58	2.65	1.1	<1	Dk. gray brown
215	90	Sand	Very fine sand	Sand	0.12	2.35	1.6	0	Gray brown
216	12	Sand	Coarse sand	Sand	0.76	0.60	0.1	0	Lt. brown gray
217	34	Sand	Fine sand	Gravelly sand	1.42	2.65	0.1	2	Pale olive
218	42	Sand	Fine sand	Sand	0.29	0.45	0.4	<1	Olive gray
219	44	Sand	Fine sand	Sand	0.22	0.60	0.4	<1	Olive gray
220	52	Sand	Fine sand	Sand	0.19	0.50	0.4	<1	Olive gray
221	64	Sand	Fine sand	Sand	0.29	0.70	0.2	1	Olive gray
222	79	Sand	Fine sand	Gravelly sand	0.36	2.20	0.4	1	Olive gray
223	84	Sand	Fine sand	Sand	0.36	1.70	0.5	<1	Dk. gray brown
224	89	Sand	Fine sand	Sand	0.44	1.85	0.3	<1	Gray brown
225	86	Sand	Fine sand	Gravelly sand	0.82	2.40	0.1	1	Brown
226	62	Sand	Fine sand	Sand	0.44	1.55	0.2	13	Brown
227	22	Gravel	Gravel	Gravel	8.60	2.00	<0.1	4	Gray brown
228	18	Gravel	Gravel	Gravel	22.75	0.00	<0.1	6	Lt. yellowish brown
229	16	Gravel	Gravel	Sandy gravel	9.20	2.40	<0.1	1	Light gray

Generally the clays are found in the deepest part of this basin and silts in slightly shallower depths. Gravels are encountered in small patches in the shallower sections of Great South Channel and on the north-central part of the bank. The largest expanse of gravel is found on the northeastern end of the bank. In this area a band of gravel extends along the northeast perimeter out to the bank's eastern end and throughout most of Eastern Channel to the southwestern corner of Browns Bank.

Predominant Fractions—The second classification of sediment types to be considered, and intermediate in degree of refinement, is a group of categories termed predominant

fractions. The particle-size category constituting the largest portion of the sediment sample is designated as the predominant fraction. With the exception of gravels, Wentworth size classes listed in table 1 are utilized for this classification; gravels have been grouped together because of the small number of samples representing most classes of gravels. In column 4 of table 2 is listed the predominant fraction of each sediment sample. The geographic distribution of these fractions is illustrated in figure 3.

The geographic pattern of predominant fractions is similar to that of grades. With relatively few exceptions the sediments in Great South Channel and over most of Georges Bank were predominantly sand fractions. Silt and clay fractions occurred only in the deep-water area northwest of the bank. Comparatively small patches of gravel were found in the central and western part of Great South Channel and along the northern and northeastern edges of Georges Bank.

The predominant fraction having widest distribution in the study area is medium sand (0.25–0.50 mm). This occurred over broad expanses of Georges Bank and covered an exceptionally large portion of the bank, especially in the shallower sections. Fine sand (0.125–0.25 mm) was common along the bank's periphery except on the eastern end. In addition, a tongue of fine sand extended northward onto the bank from the southern edge. Very fine sand (0.062–0.125 mm) was encountered in relatively small areas in three localities: southeastern Great South Channel, northwestern Great South Channel, and at one station in the deep water along the bank's northern edge. Coarse sand (0.5–1.0 mm) was moderately common, especially in relatively shallow water. It occurred in rather narrow strips and small pockets in Great South Channel and along the bank's perimeter.

Clay fractions predominated in the central portion of the deep water basin northwest of Georges Bank. Water depths in this vicinity ranged from approximately 100 to 120 fathoms. Also, in somewhat shallower water, a narrow band of clay was found close to the basin but was separated from the main tract of clay by a band of silt. Silt fractions were most common in this deep water section northwest of the bank, usually adjacent to, or close by, the clay fractions. In addition to its occurrence in this area, silt fractions predominated at two other localities. Two very small pockets of silt were found, one on the southern part of Great South Channel, and the other on the north-central perimeter of the bank.

Textural Classes—The third level of classification of sediment types discussed in this report, and the most refined of the three, is termed textural classes. This is essentially a modification of the first classification (Grades). The most abundant grade, based on weight, is complemented by the second ranking grade, and the result is a binary term expressing the two major constituents of each sediment. An exception to this rule is when one grade makes up 75 percent or more of any one sample. In such instances the term is limited to a single grade. Among the samples analyzed, gravel and sand are the only two classes that fall in this category. In cases where three grades each provide 20 percent or more of the entire sample, all three grades are identified in the textural class terms. Sand-silt-clay is the only representative of this type of textural class encountered in this study. This procedure is in accordance with the system devised by Shepard (1953). The textural class of each sediment is listed in column 5 of table 2; the geographic distribution is illustrated in figure 4.

Undoubtedly the most striking feature of the textural class distribution is the predominance of sand over a large portion of Georges Bank and adjacent areas. The sediments of the entire southern and central parts of the bank, plus large sections in Great South Channel and the northern portion of Georges Bank, come under the textural-class category of sand. As previously stated, a sediment must consist of 75 percent or more of sand to be included in this class.

A second major feature shown in figure 4 is the rather extensive areas where gravels and mixtures of sand and gravel predominate. Gravels are widely distributed over the northeast end of Georges Bank and in Eastern Channel. This large gravel area is nearly surrounded by sandy gravel or gravelly sand sediments, the latter occurring

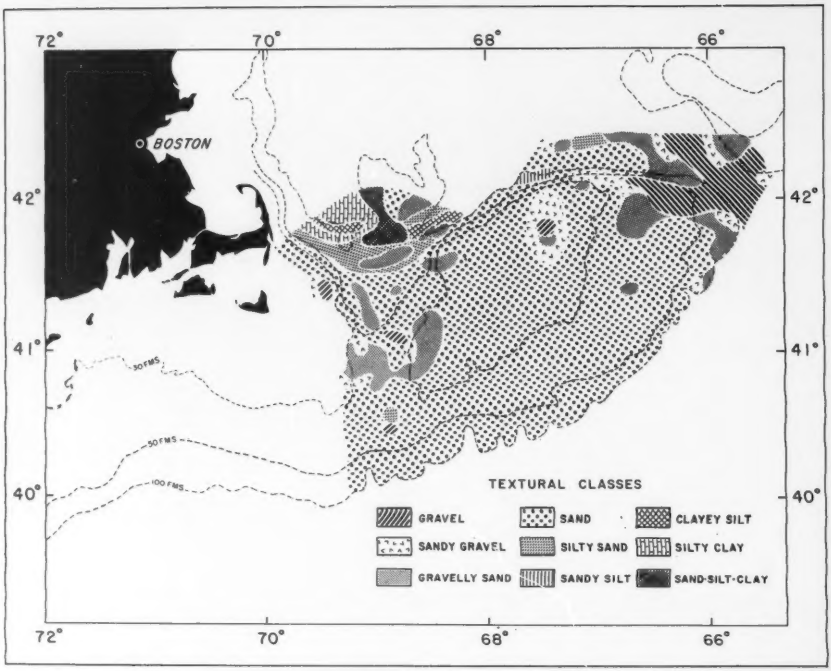

FIG. 4.—Geographic distribution of sediment textural classes.

over a much larger area than the former. Small tracts of gravel occur in Great South Channel and in the north-central part of the bank. Sandy gravel sediments in areas other than those just mentioned are relatively uncommon. Only small tracts are found in Great South Channel and the north-central part of the bank. Gravelly sand sediments occur over rather large areas throughout central and northern Great South Channel, in addition to its occurrence on the bank's eastern end.

Silts and clays and mixtures thereof abound only in the deep-water sector northwest of Georges Bank. Silty clay occurs in the deepest part of the basin and clayey silts are common in slightly shoaler water. In this same vicinity, adjacent to the eastern boundary of the silty clay sediments, is a moderately large tract of sand-silt-clay. This is the only occurrence of this textural class. East of this tract is a variety of textural classes, each covering a rather small area. These sediments are: sand, gravelly sand, silty sand, and clayey silt.

Median Diameter

Sediment median diameter is the midpoint in the size distribution of a sediment sample. Half the sample weight is composed of fractions larger than the median and half of smaller fractions. The median is a more useful measure of central tendency than the mean; since it is closer to the modal diameter, it is less affected by extreme values of skewness. For each sample, two values of median diameter were computed; one in millimeter units, the other in phi (ϕ) units. These are listed in column 6 in table 2 and column 5 in the appendix, respectively, and their geographic distribution is illustrated in figure 5. The mean values are recorded in the appendix.

The median diameters range from 0.01

mm to 22.75 mm. The small values represent samples taken at stations 6, 7, 8, 10, and 11, primarily silt-clay sediments from the deep-water area northwest of Georges Bank. The high values represent samples composed largely of gravels from Eastern Channel and scattered localities in Great South Channel. In addition, a few samples with rather high median diameters were taken from north-central Georges Bank and along the northern and northeastern parts of the bank. By far the largest part of the study area is composed of sediments whose median diameters are intermediate—between 0.25 mm and 1.0 mm.

Geographically, the greatest variation in median values occurs in the vicinity of the bank's perimeter and in the deep water beyond. This suggests that sediment median diameter may be associated with depth. Further inquiry into this aspect has revealed that sediments from the western section of the study area exhibit a distinct trend of decreasing diameter as water depth increases (see figure 6). Pebbles and sands abound in the shallower waters, whereas silts and clays predominate in the deep water. However, this relationship does not apply to the sediments on eastern Georges Bank. There, pebbles and sands are the main constituents in both the shallow- and deep-water samples. Thus the median diameters of these eastern sediments are obviously not well correlated with water depth.

In general, the median particle size of a sediment may be considered indicative of the relative current velocity at the site of deposition, regardless of depth. In many instances the samples from Georges Bank and vicinity with large median diameters were taken at localities where water currents are thought to be strong. Lack of water velocity measurements prohibits detailed analysis of this aspect but, because of its

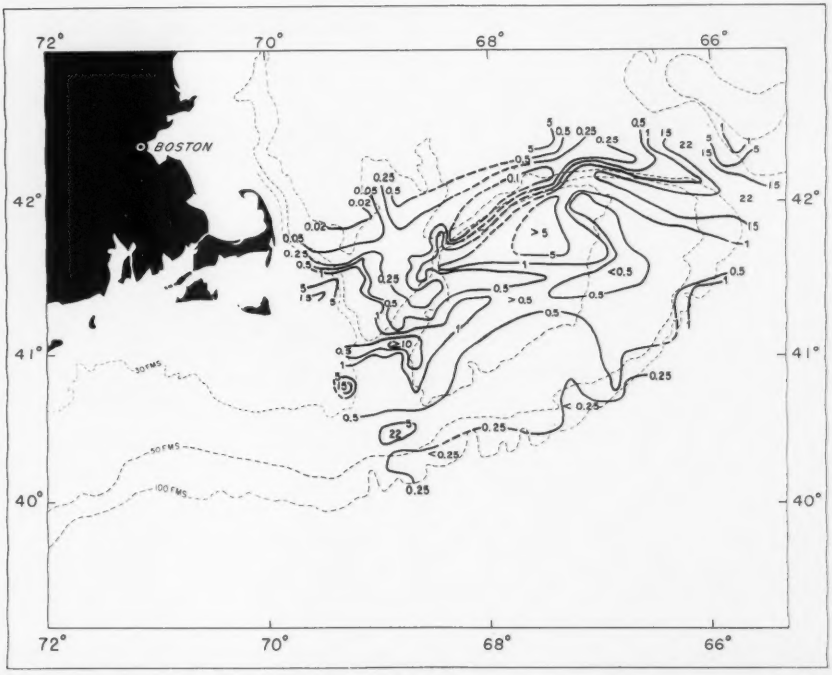

FIG. 5.—Geographic distribution of sediment median diameters. Values are given in millimeters.

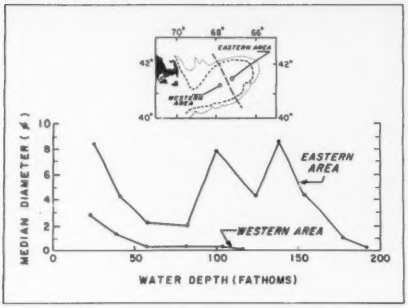

FIG. 6.—The relationship of sediment median diameter to water depth for two groups of samples: (1) eastern area, and (2) western area.

importance, a brief discussion is warranted.

Two east-west transects across Great South Channel will serve to illustrate some relationships between water depth and current velocity with sediment median diameter. The first transect, A–B in figure 7, includes stations 1 through 9. This is a series of samples taken near the coast east of Cape Cod, Massachusetts, nearly perpendicular to the gradient. Water depth at A is 15 fathoms and deepens to 122 fathoms near B and then shoals slightly to 107 fathoms at B (see figure 7). The sediment median diameter at A is 1.07 mm and decreases to 0.01 mm as B is approached, except for the increase to 0.04 mm at B. Thus, in this series the median diameter decreases as depth increases.

Another transect across Great South Channel, C–D in figure 7, reveals a distinctly different relationship between water depth and median diameter from that found at A–B. The water is relatively shallow at each end of transect C–D, 16 and 44 fathoms respectively, and is rather deep, 89 fathoms, at the center. However, the median diameter at C is large, 9.20 mm, and decreases to 0.22 mm at D. Thus the median diameter of the sediments in this area is not related to water depth. An explanation of differences in sediments taken along these two transects is provided by a study of the water currents.

In a comprehensive study of the hydrography of the Gulf of Maine, Bigelow (1927) ascertained that one exit by which water flows out of the Gulf of Maine is along the western side of Great South Channel. Another current he discusses, which is pertinent to this study, is that which flows eastward out of Nantucket Sound and subsequently turns southerly to pass across Nantucket Shoals or down through Great South Channel. Thus the existence of strong currents at A and C accounts for the large-sized sediments there, and weak currents at B and D explain the presence of fine sediments in those areas. The relationships between median diameter and degree of sorting and organic content are discussed in the following sections of this report.

Sorting

The dispersion or dimensional spread of particle sizes on either side of the mean is called sorting. The coefficient of sorting is a measure of the degree of dispersion or, as calculated in phi units, is the phi deviation measure. In column 7 of table 2 the phi deviation measure is listed for each sample, and in figure 8 the geographic distribution of these values is illustrated.

Phi deviations are utilized as an index of turbulence and variations in the velocity of water currents that transport sediments. Poorly sorted sediments, those possessing a

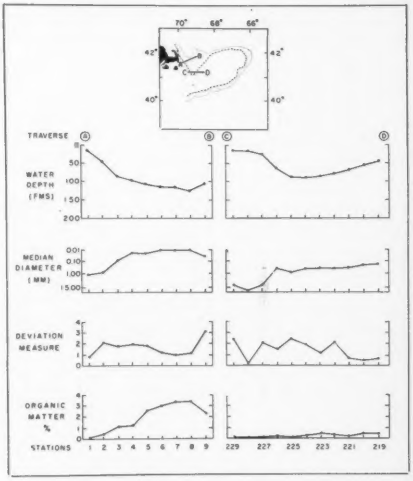

FIG. 7.—Profiles of water depth, median diameter, phi deviation measure, and organic matter at transects A–B and C–D across Great South Channel.

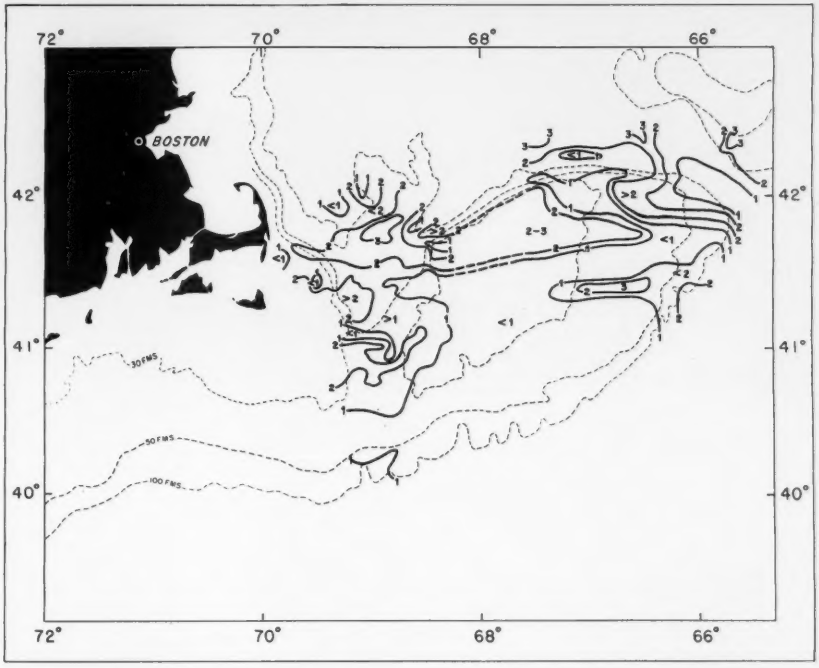

FIG. 8.—Geographic distribution of sediment phi deviation measure (sorting).

wide range in particle sizes, indicate a variable or turbulent current during deposition. Well sorted sediments are an indication of smooth, stable currents.

Georges Bank sediments range from perfectly sorted (0 phi deviation) to very poorly sorted (4.5 phi deviation). A large section in the central and southern parts of the bank contains sediments that are well sorted, having phi deviations of 1.0 or less. Much of this area has sediments that are very well sorted, having phi deviations of 0.5 or less. Small sections along the northern part of the bank and in both channels also have well sorted sediments. Poorly sorted sediments occur chiefly in the channel areas and along the bank's northern edge. It is of interest to note that some of the predominantly fine sediments in the deep-water area northwest of Georges Bank are poorly sorted as are many of the coarse sediments in the channel areas.

Since the phi deviation measure is an index of turbulence or variation in current velocities, the following inferences are drawn: (1) Turbulent and/or variable currents occur in Great South Channel, along much of northern Georges Bank, and in the eastern half of Eastern Channel. (2) Relatively steady and uniform currents prevail over the central and southern parts of Georges Bank.

In areas where the surface- or mid-water currents strike the sea bed, turbulence and/or variations in current velocity are greatest. This is noticeably so in the shallowest section of Great South Channel, in the shoaling area north of Great South Channel, and in the shallows of north-central and northeastern parts of Georges Bank. Also, of particular interest, are indications of a turbulent or variable current flowing westward in the vicinity of Corsair Canyon (41°25′ N., 66°10′ W.).

Phi deviation is not closely associated with water depth, median diameter, or

organic content. See figure 7 for a few illustrations. There is a trend for shallow water sediments to be better sorted than those from deep water, all samples considered. This relationship does not, however, hold for all sections of the study area.

Organic Content

Organic content of Georges Bank sediments ranges from 0 to 3.4 percent by weight. In general, high values are associated with fine-grained sediments and deep water; low values are associated with coarse-grained sediments and relatively shallow water. There is an apparent trend for deep water sediments near shore to contain more organic matter than samples taken at similar depths farther from shore.

The quantitative geographic distribution of sediment organic matter is illustrated in figure 9. Sediments with highest organic content occurred in the deep-water (greater than 100 fathoms) basin northwest of Georges Bank. Sediments in this area are composed predominantly of silts and clays, with a median particle size less than 0.05 mm. The organic content in these samples ranges from 3.0 to 3.4 percent. In somewhat shallower water adjacent to this basin the sediment organic content is, on the average, between 0.5 and 3.0 percent. The lower values usually occur at the shallower depths.

North of Great South Channel and Georges Bank in water depths greater than 100 fathoms, there is a striking offshore (west to east) gradient in organic content. Sediment samples taken farthest offshore are markedly lower in organic content than samples taken nearer the Massachusetts coast. Organic matter in near shore samples ranges from 2.2 to 3.4 percent, compared to 0.1 percent or less in the easternmost samples.

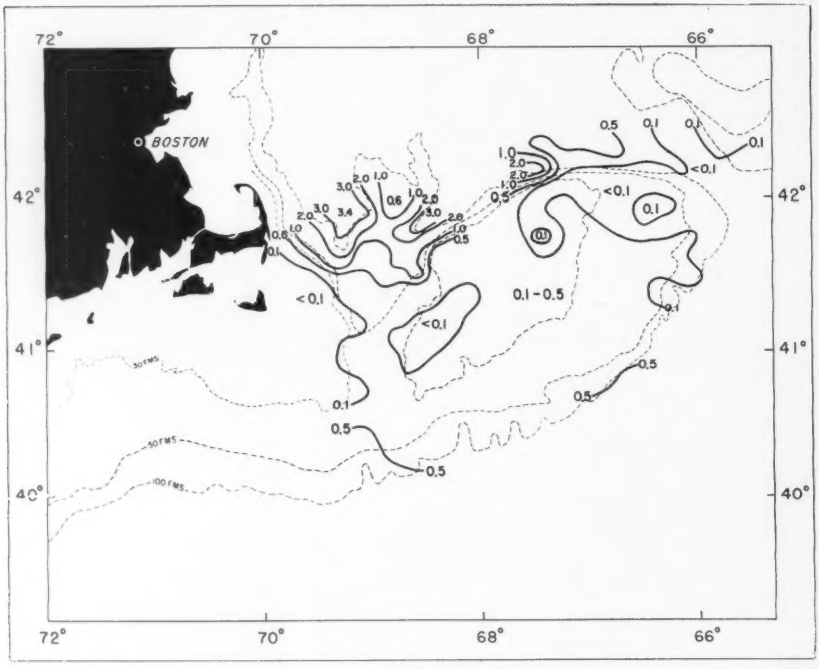

FIG. 9.—Quantitative geographic distribution of sediment organic matter. Values are given in percentage weight.

Relationship with Water Depth—The relationship between water depth and sediment organic content is difficult to assess from the isopleth chart shown in figure 9, because of geographic variations. A summation of the same data upon which the chart is based is listed in table 3. The mean organic content for each 25-fathom depth class is listed separately for both the eastern and western halves of the study area (see inset in figure 6 for division between the eastern and western sections). This tabulation shows clearly the relationship of organic matter and water depth, and also the difference in degree of correlation in this relationship between the eastern and western sections.

On Georges Bank proper, nearly all sediments contain less than 1.0 percent organic matter. Moreover, it is 0.2 percent or less in more than 85 percent of all sediment samples taken within the bank's 50-fathom isobath. Organic content of 0.1 and 0.2 percent are by far the most common values for Georges Bank sediments. Two areas where sediments are especially low, less than 0.1 percent, in organic matter are: (1) the bank's northeastern end, and (2) a small sector in the shallow part of southwestern Georges Bank.

In Eastern Channel and southwestern Browns Bank the sediment organic content is also very low—0.1 percent or less. Sediments from the shallow portion of Great South Channel are likewise low in organic matter, ranging from 0.2 to less than 0.1 percent. However, in the southern part of this channel, in water depths between 40 and 100 fathoms, the organic content is slightly higher, containing 0.4 to 0.7 percent.

In the western half of the study area there is a pronounced increase in organic content with increased depth of water. This same trend exists in the eastern half, but the increment is exceedingly small. In the western section the organic matter ranges in quantity from 0.1 percent in the 0–24 fathom depth class to 2.5 percent in the 100–124 fathom depth class. In the eastern section it gradually increases from 0.1 percent in the 0–24 fathom depth class to only 0.4 percent in the 175–199 fathom depth class.

Two principal factors that affect the quantity of organic matter in bottom sediments are (1) water currents and (2) oxygen content of the overlying water (Trask, 1939; Richards and Redfield, 1954). In the Georges Bank area, water currents appear to be the primary determinant. Rather strong currents prevail over the shallow portions of the bank and also over the bank's eastern end and adjacent deep water (Bigelow, 1927). In these same areas the sediment organic content is low. The areas where the organic content is high—the deep water section northwest of Georges Bank—are areas where bottom water currents are weak.

TABLE 3.—*Mean sediment organic content in eastern and western sections of the study area*

Water depth class (fathoms)	Mean organic content (percentage weight)	
	Eastern	Western
0–24	0.1	0.1
25–49	0.1	0.2
50–74	0.1	0.4
75–99	0.2	1.0
100–124	0.1	2.5
125–149	0.4	—
150–174	0.4	—
175–199	0.4	—

Oxygen content of the water just above the sediments also appears to play an important role in affecting the variations in amount of sediment organic matter from place to place in the Georges Bank region. Oxygen content of bottom water (Rakestraw, 1933) on Georges Bank is significantly higher than bottom water in the southern Gulf of Maine. Also, there is more rapid replenishment of oxygen in bottom water on Georges Bank than in the adjacent deep-water north of the bank. Thus the decomposition of organic matter on Georges Bank would be accelerated by the higher oxygen concentration. It is concluded that oxygen and water currents are two of the principal factors producing the wide geographic variations in sediment organic content observed in this area.

Relationship with Sediment Particle Size—The physical factors involved in the deposition and erosion of sediments likewise affect the deposition of organic matter. This results in a close correlation between organic content and sediment particle size. In the Georges Bank area, as in most others, organic content is high in fine-grained sediments and low in coarse-grained sediments.

TABLE 4.—*Relationship between sediment particle size and quantity of organic matter*

Median particle size (mm)	Organic matter (percent)	Number of samples
0.01	3.27	3
0.02	2.40	5
0.07	1.70	5
0.16	0.83	15
0.25	0.50	30
0.35	0.29	24
0.44	0.22	14
0.69	0.22	63
1.31	0.09	25
2.14	0.08	4
3.36	0.08	2
4.93	0.13	6
8.92	0.06	6
12.34	0.10	6
15.00	0.10	1
18.50	0.06	6
22.75	0.06	8

This is evident from table 4, where percentage organic content is listed opposite median particle size. This relationship is significant only in those sediments having a median diameter less than about 2 mm. In sediments with a median diameter 2 mm or more, there is little change in organic content associated with an increase in diameter. A decrease in median diameter from 2.0 to 0.5 mm is accompanied by a slight increase in organic matter, from 0.08 to 0.20 percent. In contrast to this, a sharp increase in organic content, from 0.2 to 3.3 percent, is associated with a decrease in median diameter from 0.5 to 0.01 mm.

Additional evidence on this subject is shown in figure 7, in which profiles of sediment median diameter and organic content are plotted for two transects across Great South Channel. Although variations occur, the general trend described above is evident.

Shell Content

Mollusk shell fragments constitute a significant portion of the sediments in some localities and, due to their peculiar physical characteristics, they are of special importance from the biological standpoint. For example, certain species of tube-building polychaete worms select only mollusk shell fragments from the sediment for tube construction. The measure of shell content derived from this study are minimum values only, inasmuch as they are based on fragments 2 mm in diameter or larger. Obviously smaller particles of shell are present in the sediments, but the additional labor required to obtain more refined values was not warranted. Shell content values are expressed as percentage weight of the total sediment sample. Values for each sample are listed in column 9 of table 2, and illustrated in figure 10.

Shell fractions in the sediment samples range from 0 to 25 percent. Shell is most prevalent in sediments from the eastern part of Georges Bank. A rather broad band across the bank's eastern end, extending from the northern edge southward and westward to the southern edge, encompasses an area where most of the sediments consist of 5 to 25 percent shell. Relatively high percentages of shell also occur at a few localized areas in Great South Channel. Sediments in the central and western parts of Georges Bank are composed of rather small quantities of shell, generally less than 2 percent. In water depths greater than 75 fathoms along the entire northern edge, shell fragments are very sparse or absent. The geographic distribution of shell fragments agrees rather closely with the occurrence of sea scallop (*Placopecten magellanicus*) beds. The sea scallop is the only shellfish currently being fished commercially on this bank.

The relationship between water depth and shell content is shown in figure 11. It is apparent from this graph that shell fragments are most abundant in sediments occurring between 15 and 75 fathoms in depth. In depths greater than 75 fathoms the quantity of shell is consistently very low, less than 0.1 percent in most cases.

Color

Variations in sediment color from white to dark gray brown are found distributed in a somewhat random pattern over the entire area studied (see column 10 in table 2). Browns, grays, and combinations of the two colors are especially common. There is a trend for the light colored sediments, such as white and yellow, to be more common in the central and south central parts of Georges Bank. Darker sediments are predominant in

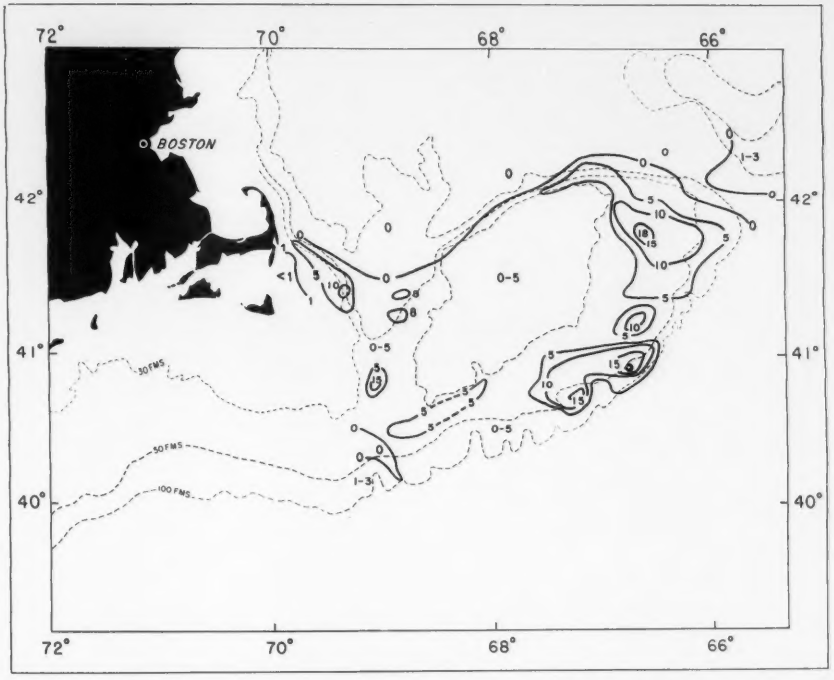

FIG. 10.—Quantitative geographic distribution of mollusk shell fragments. Values are given in percentage weight.

the channels and deep-water areas. Sediments with high organic content are generally gray in color, but this relationship is not consistent. There is no distinct association between color and particle size or other sediment parameters.

DISCUSSION

Georges Bank sediments consist mainly of sand of various sizes. This material is mostly glacial debris. At the present time very little new sediment is being deposited on the bank proper. Silts and clays of terrigenous origin, which may be expected to be discharged from rivers in northern New England and southeastern Canada and carried to the bank in suspension, appear to be effectively trapped in the Gulf of Maine basin before reaching the bank. Changes in sediment distribution now taking place result primarily from the shifting and remolding of material already present on the bank.

The generalization that sediments are finer in the deep water farther from land

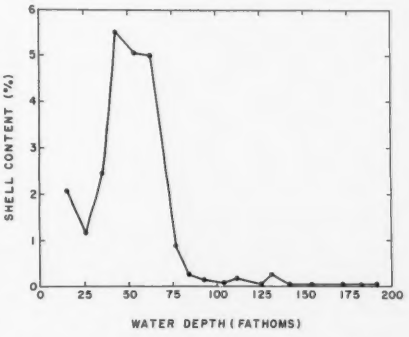

FIG. 11.—Relationship between water depth and sediment shell content.

than those occurring in shallower water close to shore, does not apply to the Georges Bank area. Some strikingly different relationships between sediment particle-size and water depth and distance from land are illustrated in figure 12. Two transects of sediment samples extending from shallow to deep water, one near-shore and one offshore, reveal nearly opposite trends in size distribution versus water depth. In this figure the particle-size frequency distributions are illustrated in their respective positions below the water depth profile. These examples are based on sediments taken at stations 1–9 for the near-shore transect, and from stations 162–153 for the offshore transect (see inset in figure 12 for locations).

From figure 12 it can be seen that in near-

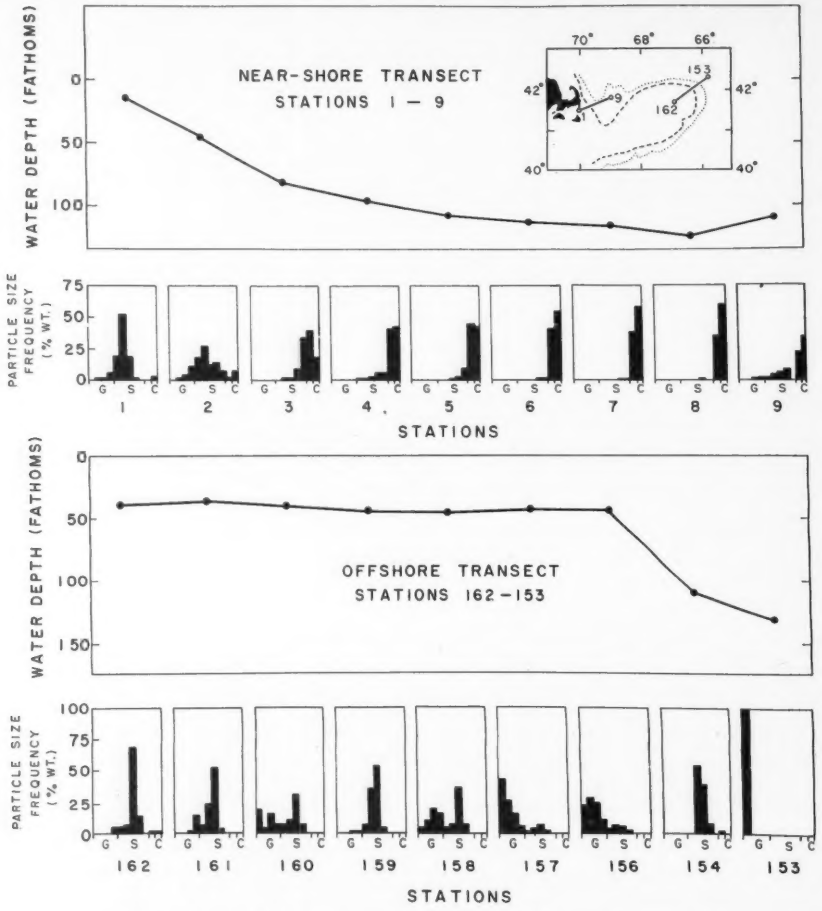

FIG. 12.—Sediment particle size in relation to water depth for samples from two transects, (1) near-shore and (2) offshore, extending from shallow to deep water. Abbreviations of sediment fractions are: gravel—G, sand—S, and clay—C.

shore sediments, gravel and sand predominate in samples from shallow water, and silt and clay successively increase in deeper water samples. At stations 6, 7, and 8 the sediments are very similar to one another, each consisting predominantly of clay with silt ranking second. Another feature revealed by this figure is the increase in sand and gravel at station 9, where the water depth is slightly less than at preceding stations.

Sediments taken along the offshore transect exhibit a trend distinctly opposite to the foregoing. Shallow water sediments are generally finer than those from the deep water. At the shallow water stations (162–156), in depths of approximately 40 fathoms, the sediment is composed largely of sand and gravel, plus small quantities of silt and clay. At the deepest station (153), in 129 fathoms, the substrate is entirely gravel.

Our knowledge of the hydrography of the Georges Bank area, especially in regard to current velocity of bottom water, is still too imperfect to adequately understand the relationships between water movement and sedimentation. It is known that wave action extends to the bottom over most of Georges Bank in winter, and that tidal currents are exceptionally strong on the bank's shallower portions throughout the year. The effectiveness of the combination of wave action and tidal currents in sorting bottom deposits in the shallower parts of the bank is indicated by the large expanse of central and southern Georges Bank where sediments are very well sorted. In some deep-water areas, especially in and near the channels at the eastern and western ends of the bank, the non-tidal current is probably the main sorting agent.

Further evidence of complex sedimentary processes associated with hydrographic conditions is evident from the geographic distribution of organic matter. Sediment organic content is low not only in the shallow portions of Georges Bank, where wave action and tidal currents are operative, but also in some deep-water areas adjacent to the bank.

SUMMARY

1.—Sand is by far the most prevalent sediment on Georges Bank and vicinity. Gravels are common in the channels and on the northern and eastern parts of the bank. Silts and clays are predominant only in the deep-water basin northwest of Georges Bank.

2.—Sediment median diameters ranged from 0.01 to 22.75 mm. A large portion of the study area contains sediments whose median diameters are between 0.25 and 1.0 mm. Greatest variation in median diameters occurs in the channel areas and along the bank's northern periphery.

3.—Natural sorting of the sediment fractions ranges from poorly sorted to perfectly sorted. Poorly sorted sediments predominate in the channels and on the northern edge of Georges Bank. Well sorted sediments occur over a large area in the central and southern sections of Georges Bank, and small patches are found in the channel areas and along the bank's northern edge.

4.—Organic content varies directly with the sediment silt-clay content. The organic content ranges from 0 to 3.4 percent, and is highest in the silt-clay sediments northwest of Georges Bank. Generally, very small quantities (less than 0.5 percent) of organic matter are present in the sediments on Georges Bank proper.

5.—Mollusk shell fragments comprise a significant portion of the sediments in some localities. They are especially common in a north-south band extending across the eastern end of Georges Bank. Sediments with as much as 25 percent shell are found in this area. Over most of the bank the sediments contain less than 2 percent shell, and in deep water the shell content is nil.

6.—A rather wide variety of sediment colors was observed. They range from white to dark gray brown. Brown and gray and combinations of these two colors are most common.

ACKNOWLEDGMENTS

I wish to thank Dr. Robert L. McMaster, Narragansett Marine Laboratory, and Dr. H. T. Greweling, N. Y. State College of Agriculture, for helpful suggestions and advice.

APPENDIX

TABLE A.—*Coordinates of latitude and longitude for each station, and the sediment particle-size distribution mean, kurtosis and two measures of skewness*

Station Number	Station Latitude (North)	Location Longitude (West)	Sediment sample parameters				
			Mean diameter ($M\phi$)	Median diameter ($Md\phi$)	Skewness ($\alpha_{1\phi}$)	Skewness ($\alpha_{2\phi}$)	Kurtosis (β_ϕ)
1	41°36′	69°47′	−0.15	−0.10	−0.06	−0.39	1.08
2	41°40′	69°42′	0.55	0.20	0.17	1.41	1.63
3	41°42′	69°38′	4.45	3.90	0.31	0.69	0.60
4	41°46′	69°33′	5.45	5.80	−0.18	−0.44	0.67
5	41°48′	69°28′	5.70	5.80	−0.06	−0.11	0.56
6	41°51′	69°22′	6.15	6.20	−0.04	−0.26	0.82
7	41°55′	69°15′	6.30	6.20	0.11	−0.06	0.28
8	41°57′	69°10′	6.35	6.40	−0.04	−0.13	0.60
9	42°00′	69°05′	3.20	4.60	−0.45	−0.68	0.61
10	41°54′	69°05′	5.95	6.10	−0.09	−0.14	0.23
11	41°49′	69°05′	5.80	5.70	0.56	0.03	0.25
12	41°45′	69°04′	3.95	4.00	−0.02	−0.46	0.73
13	41°39′	69°06′	1.85	1.60	0.12	0.56	1.09
14	41°34′	69°06′	0.65	1.20	−0.17	−0.14	1.02
15	41°30′	69°05′	0.90	1.00	−0.13	−0.44	0.81
16	41°25′	69°06′	−0.55	−0.20	−0.14	0.06	0.67
17	41°19′	69°05′	−1.55	−2.10	0.20	0.47	0.40
18	41°14′	69°05′	0.15	0.60	−0.21	0.33	1.37
19	41°09′	69°04′	−0.75	−0.30	−0.23	−0.31	0.38
20	41°05′	69°05′	0.35	0.50	−0.43	−0.86	1.00
21	40°59′	69°06′	−0.80	0.90	−0.81	−0.90	0.33
22	40°54′	69°05′	−1.65	−1.20	−0.16	−0.14	0.16
23	40°48′	69°04′	−1.85	−2.50	0.22	0.27	0.11
24	40°43′	69°04′	−0.80	−0.10	−0.41	−0.59	0.47
25	40°38′	69°04′	−0.60	0.70	−0.68	−0.76	0.50
26	40°33′	69°06′	1.50	1.50	0.00	−0.20	1.00
27	40°29′	69°06′	2.55	2.40	1.00	7.00	6.00
28	40°24′	69°06′	2.70	2.50	0.50	2.63	2.88
29	40°19′	69°05′	2.70	2.70	0.00	2.40	2.40
30	40°14′	69°05′	2.25	2.80	−1.00	0.27	3.45
31	40°10′	69°05′	2.00	2.20	−0.13	0.06	1.00
32	40°09′	68°58′	2.30	2.60	−0.25	−0.88	1.54
33	40°09′	68°50′	2.15	2.10	0.77	1.15	1.85
34	40°15′	68°50′	1.75	1.80	−0.05	0.43	0.76
35	40°20′	68°51′	1.80	1.90	−0.11	−0.06	0.61
36	40°26′	68°51′	2.30	2.30	0.00	0.66	1.33
37	40°29′	68°52′	−4.50	−4.50	0.00	0.00	−1.00
38	40°34′	68°51′	3.55	2.20	0.69	0.74	0.15
39	40°39′	68°51′	−0.20	0.60	−0.42	−0.58	0.32
40	40°44′	68°51′	−1.00	0.50	−0.79	−1.08	0.50
41	40°52′	68°50′	−1.15	0.90	−0.80	0.90	0.25
42	40°55′	68°50′	−0.55	0.60	−0.11	−0.56	1.56
43	41°00′	68°50′	0.10	0.50	−0.36	−0.68	0.59
44	41°05′	68°50′	−3.45	−3.50	0.05	1.67	1.62
45	41°10′	68°50′	0.60	1.30	−0.54	−1.11	0.88
46	41°15′	68°50′	0.10	1.20	−0.69	−1.31	0.88
47	41°20′	68°50′	1.25	1.80	−0.48	−1.26	1.13
48	41°25′	68°50′	2.30	2.20	0.20	0.60	1.00
49	41°30′	68°50′	1.75	2.60	−0.59	0.10	1.17
50	41°34′	68°50′	2.90	3.20	−0.21	−0.39	1.96
51	41°39′	68°50′	1.70	2.40	−0.26	−0.04	0.66
52	41°44′	68°50′	3.35	3.60	−0.08	−0.33	0.66
53	41°50′	68°50′	2.45	2.00	0.12	0.15	0.30
54	41°54′	68°50′	0.85	0.60	0.19	1.44	1.93
55	42°00′	68°50′	1.40	1.30	0.06	0.63	1.44
56	41°55′	68°46′	0.80	0.60	0.07	0.50	0.69

TABLE A.—*Continued*

Station Number	Station Latitude (North)	Location Longitude (West)	Sediment sample parameters				
			Mean diameter ($M\phi$)	Median diameter ($Md\phi$)	Skewness ($\alpha_{1\phi}$)	Skewness ($\alpha_{2\phi}$)	Kurtosis (β_ϕ)
57	41°52′	68°42′	2.75	2.00	0.26	0.28	0.51
58	41°47′	68°38′	3.05	3.10	−0.08	−0.08	1.08
59	41°42′	68°35′	4.15	3.60	0.44	1.12	0.92
60	41°39′	68°30′	2.00	1.40	0.27	0.70	0.93
61	41°35′	68°26′	−0.15	0.30	−0.24	−0.27	0.35
62	41°31′	68°23′	−0.25	1.10	−0.60	−0.93	0.44
63	41°26′	69°19′	1.70	1.50	1.00	2.25	1.25
64	41°22′	68°20′	−0.05	0.00	−0.11	−0.22	1.00
65	41°18′	68°11′	−0.35	−0.40	0.20	0.40	1.80
66	41°14′	68°07′	0.75	0.90	−0.27	−1.18	1.45
67	41°10′	68°03′	0.50	0.60	−0.25	−0.25	0.75
68	41°06′	68°00′	1.10	1.50	−4.00	5.00	4.00
69	41°02′	67°56′	1.70	1.90	−0.67	−0.50	1.17
70	40°57′	67°52′	2.00	2.00	0.00	−0.33	1.00
71	40°53′	67°48′	0.95	0.80	0.18	0.24	0.76
72	40°49′	67°49′	0.80	1.00	−0.36	−0.55	1.18
73	40°45′	67°40′	1.05	1.00	0.07	0.13	0.87
74	40°41′	67°36′	1.85	2.10	−0.29	−0.41	1.06
75	40°36′	67°33′	0.95	1.00	−0.09	−0.27	1.09
76	40°32′	67°33′	0.55	1.00	−0.47	−0.37	0.95
78	40°33′	67°28′	1.40	1.40	0.00	0.06	0.69
79	40°37′	67°28′	0.25	0.30	−0.08	−0.31	1.15
80	40°43′	67°29′	1.45	1.40	0.06	0.18	0.59
81	40°48′	67°23′	1.50	1.40	0.13	0.00	0.75
82	40°53′	67°28′	1.65	1.70	−0.08	0.00	1.31
83	40°59′	67°28′	1.25	1.50	−0.45	0.36	1.18
84	41°04′	67°28′	1.35	1.40	−0.09	0.00	0.64
85	41°09′	67°28′	1.80	1.90	−0.25	−0.50	0.75
86	41°14′	67°28′	1.55	1.50	0.14	0.14	0.86
87	41°19′	67°28′	0.40	0.50	−0.13	−0.25	0.50
88	41°24′	67°28′	0.80	1.10	−0.60	−1.40	1.20
89	41°29′	67°28′	1.05	1.00	0.11	0.33	0.67
90	41°34′	67°28′	−0.10	0.30	−0.50	−0.75	0.75
91	41°39′	67°28′	−1.80	−4.20	0.89	0.94	0.06
92	41°44′	67°28′	−0.60	−0.50	−0.05	−0.13	0.48
93	41°49′	67°28′	−2.15	−3.70	0.66	0.89	0.23
94	41°54′	67°28′	−1.20	−2.40	0.50	0.48	0.19
95	42°01′	67°27′	−2.00	−3.40	0.56	0.70	0.14
96	42°05′	67°28′	−0.20	0.60	−0.42	−0.37	0.26
97	42°08′	67°28′	2.55	2.30	0.33	0.87	0.80
98	42°10′	67°28′	4.55	3.90	0.39	0.76	0.55
99	42°16′	67°27′	2.65	1.90	0.33	0.62	0.69
100	42°20′	67°28′	−1.30	−3.70	0.75	0.97	0.59
101	42°20′	67°20′	0.75	1.70	−0.33	−0.47	0.53
102	42°20′	67°10′	2.15	2.50	−0.14	−0.39	1.06
103	42°15′	67°10′	2.00	2.00	0.00	1.00	1.00
104	42°10′	67°10′	−1.85	−3.90	0.77	1.02	0.25
105	42°07′	67°09′	−0.60	−0.40	−0.18	−0.27	0.36
106	42°06′	67°09′	−1.20	−1.00	−0.12	−0.12	0.29
107	42°00′	67°10′	2.55	2.50	1.00	10.00	9.00
108	42°00′	67°04′	1.10	1.10	0.00	0.00	1.00
109	42°02′	66°58′	0.60	0.60	0.00	0.50	1.00
110	42°00′	66°56′	0.15	0.20	−0.11	−1.11	1.67
111	42°00′	66°45′	−1.00	−0.80	−0.10	0.05	0.30
112	42°05′	66°45′	−2.20	−3.70	0.65	0.91	0.26
113	42°07′	66°45′	−4.50	−4.50	0.00	0.00	0.00
114	41°10′	66°45′	−0.25	0.40	−0.62	−0.86	0.71

(*Table continues on next pages*)

TABLE A.—*Continued*

Station Number	Station Latitude (North)	Location Longitude (West)	Sediment sample parameters				
			Mean diameter ($M\phi$)	Median diameter ($Md\phi$)	Skewness ($\alpha_{1\phi}$)	Skewness ($\alpha_{2\phi}$)	Kurtosis (β_ϕ)
115	42°15′	66°45′	2.00	2.40	−0.31	−0.19	1.96
116	42°20′	66°45′	1.00	1.60	−0.25	0.06	0.77
117	42°20′	66°40′	1.45	1.80	−0.21	0.06	1.48
118	42°21′	66°31′	−1.45	−0.80	−0.21	−0.07	0.15
119	42°21′	66°26′	−1.65	−2.10	0.16	0.30	0.14
120	42°21′	66°21′	−3.35	−4.50	1.00	2.30	1.48
121	42°15′	66°21′	−0.60	0.50	−0.48	−0.65	0.52
122	42°10′	66°20′	0.00	0.70	0.00	−0.27	0.32
123	42°07′	66°20′	−1.80	−0.30	−0.56	−0.41	0.15
124	42°04′	66°20′	−2.30	−3.00	0.33	0.57	0.29
125	42°00′	66°20′	−2.95	−4.50	1.03	1.84	0.84
126	41°55′	66°20′	−2.30	−3.20	0.45	0.75	0.40
127	41°50′	66°20′	−0.55	0.10	−0.57	−0.70	0.39
128	41°45′	66°20′	0.60	0.70	−0.25	−0.50	1.00
129	41°41′	66°20′	0.45	0.60	−0.20	−0.87	1.33
130	41°35′	66°19′	0.35	0.50	−0.23	−0.54	0.92
131	41°29′	66°21′	−0.30	0.20	−0.29	−0.38	0.56
132	41°24′	66°20′	−0.05	0.50	−0.33	−0.33	0.30
133	41°24′	66°14′	1.20	1.70	−0.56	−0.72	0.39
134	41°24′	66°07′	−1.65	−1.60	−0.02	0.07	0.09
135	41°24′	66°00′	−1.05	−1.30	0.12	0.17	0.24
136	41°30′	66°00′	−0.25	0.10	0.20	−0.34	0.49
137	41°35′	66°00′	0.50	0.60	−0.17	0.08	0.58
138	41°40′	66°00′	−0.50	0.20	−0.50	0.54	0.39
139	41°45′	66°00′	0.60	0.60	0.00	−0.25	1.00
140	41°49′	65°58′	−0.65	−0.70	0.03	0.12	0.21
141	41°52′	65°54′	−2.00	−2.20	0.08	0.20	0.12
142	41°55′	65°48′	−3.50	−4.50	1.00	2.85	1.85
144	42°03′	65°39′	−4.10	−4.50	1.00	1.75	0.75
146	42°09′	65°30′	−4.10	−3.00	0.38	0.48	0.18
148	42°17′	65°38′	−2.10	−4.20	0.88	1.08	0.21
149	42°20′	65°44′	−2.10	0.50	0.38	0.48	0.18
150	42°22′	65°47′	−1.50	0.20	−0.67	0.78	0.05
151	42°18′	65°51′	−1.45	−0.80	−0.45	0.59	0.76
152	42°15′	65°56′	−1.95	−1.90	−0.03	0.05	0.23
153	42°11′	66°02′	−4.50	−4.50	—	—	—
154	42°09′	66°06′	0.80	0.50	1.00	0.20	1.00
156	42°02′	66°16′	−3.05	−3.50	0.31	1.07	0.76
157	41°57′	66°21′	−3.45	−4.20	0.71	2.43	1.71
158	41°58′	66°25′	−1.10	−1.00	−0.04	−0.17	0.26
159	41°50′	66°30′	0.45	0.60	−0.23	−0.46	0.69
160	41°46′	66°34′	−1.60	−0.60	−0.34	−0.29	0.05
161	41°42′	66°41′	−0.15	0.60	−0.65	−0.91	0.52
162	41°40′	66°45′	1.00	1.40	0.80	2.60	2.20
163	41°35′	66°45′	1.00	1.30	−0.60	2.30	2.30
164	41°29′	66°45′	1.15	1.20	−0.14	0.00	1.00
165	41°25′	66°44′	−1.45	−0.30	−0.38	0.30	0.08
166	41°19′	66°45′	0.45	0.50	−0.09	−0.27	0.91
167	41°14′	66°44′	0.95	0.90	0.11	−0.11	0.89
168	41°09′	66°45′	0.40	0.40	0.00	−0.17	0.67
169	41°05′	66°44′	0.60	0.70	−0.20	−0.60	1.20
170	40°59′	66°44′	1.45	1.40	0.14	0.14	0.86
171	40°54′	66°46′	1.40	1.50	−0.25	−0.50	1.00
172	40°49′	66°45′	2.40	2.30	0.17	0.67	0.83
173	40°49′	66°52′	0.75	0.80	−0.09	−0.09	0.73
174	40°48′	66°58′	1.85	1.90	−0.11	−0.67	0.78
175	40°48′	67°05′	1.65	1.70	−0.09	−0.36	0.82
176	47°47′	67°12′	2.10	2.00	0.20	1.00	1.00

TABLE A.—*Continued*

Station Number	Station Latitude (North)	Location Longitude (West)	Sediment sample parameters				
			Mean diameter ($M\phi$)	Median diameter ($Md\phi$)	Skewness ($\alpha_{1\phi}$)	Skewness ($\alpha_{2\phi}$)	Kurtosis (β_ϕ)
177	40°46′	67°18′	2.10	2.20	−0.14	−0.28	0.71
178	40°46′	67°25′	1.60	1.50	0.13	0.19	0.81
179	40°46′	67°32′	1.45	1.50	−0.06	0.18	0.59
180	40°46′	67°37′	0.60	0.60	0.00	0.64	0.50
181	40°46′	67°45′	−0.30	0.10	−0.33	−0.29	0.54
182	40°46′	67°52′	1.25	1.30	−0.11	0.00	0.78
183	40°48′	67°58′	1.75	1.80	−0.11	−0.44	1.00
184	40°48′	68°06′	1.65	1.80	−0.27	−0.55	0.64
185	40°48′	68°12′	1.95	1.90	0.20	0.80	1.40
186	40°48′	68°19′	1.70	1.60	0.33	1.00	1.00
187	40°48′	68°25′	0.20	0.30	−0.25	−0.38	0.63
188	40°48′	68°32′	0.90	1.00	−0.20	−0.30	0.90
189	40°48′	68°40′	−0.55	−0.20	−0.23	−0.13	0.55
190	40°48′	68°46′	0.70	0.50	0.22	0.33	0.56
191	40°48′	68°59′	−0.60	0.70	−0.54	−0.67	0.38
192	40°48′	69°02′	1.00	1.10	−0.17	−2.50	3.00
193	40°48′	69°06′	−0.30	0.00	−0.38	−0.56	0.69
194	40°48′	69°13′	1.20	0.00	−0.57	−0.62	0.24
195	40°48′	69°15′	−2.05	−4.20	0.88	1.04	0.16
196	40°52′	69°15′	−1.15	0.70	−0.76	−0.88	0.20
197	40°58′	69°15′	−1.25	−0.40	−0.33	−0.33	0.27
198	41°00′	69°15′	−0.60	−0.40	−0.48	−0.57	0.38
199	41°00′	69°08′	−2.50	−3.60	0.38	0.41	0.31
200	41°00′	69°02′	−1.10	0.30	−0.64	−0.61	0.30
201	41°00′	68°55′	−1.00	−0.40	−0.24	−0.26	0.26
202	41°00′	68°48′	0.35	0.30	0.07	3.87	4.73
203	41°00′	68°42′	−2.05	−2.50	0.20	0.47	0.36
204	41°00′	68°35′	−0.75	−0.40	−0.19	−0.30	0.32
205	41°05′	68°35′	−1.05	0.00	−0.45	−0.53	0.26
206	41°10′	68°35′	−1.20	−0.60	−0.32	−0.32	0.21
207	41°15′	68°35′	−0.50	1.20	−0.77	−0.80	0.34
208	41°20′	68°35′	2.80	2.30	0.83	3.83	4.67
209	41°25′	68°35′	2.35	2.50	−0.27	3.00	5.64
210	41°30′	68°35′	1.00	0.60	0.24	0.26	0.26
211	41°34′	68°34′	0.65	0.80	−0.05	0.51	1.09
213	41°45′	68°34′	1.70	2.10	0.18	0.32	1.36
214	41°45′	68°28′	1.15	0.80	0.13	0.15	1.15
215	41°45′	68°22′	3.65	3.10	0.23	0.60	0.79
216	41°40′	68°24′	0.50	0.40	0.17	0.92	1.25
217	41°34′	68°25′	−0.75	−0.50	−0.09	−0.15	0.25
218	41°30′	68°28′	1.95	1.80	0.33	1.22	0.89
219	41°24′	68°31′	1.90	2.20	−0.50	−2.58	3.42
220	41°25′	68°37′	2.20	2.40	−0.40	−1.00	1.80
221	41°25′	68°44′	2.10	1.80	0.43	0.57	0.86
222	41°25′	68°50′	0.50	1.50	−0.46	−0.48	0.39
223	41°25′	68°57′	1.20	1.50	−0.18	0.38	1.62
224	41°25′	69°05′	0.45	1.20	−0.41	0.30	1.30
225	41°25′	69°12′	−0.50	0.30	−0.33	−0.29	0.40
226	41°25′	69°18′	0.85	1.20	−0.23	−0.58	0.81
227	41°25′	69°25′	−2.50	−3.10	0.30	0.58	0.28
228	41°25′	69°30′	−4.50	−4.50	0.00	0.00	−1.00
229	41°25′	69°34′	−2.10	−3.20	0.46	0.61	−0.06

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 31, NO. 2, PP. 189–195
FIGS. 1–3, JUNE, 1961

EVAPORITE SOLUTION BRECCIAS FROM THE MISSISSIPPIAN OF SOUTHWEST MONTANA[1]

GERARD V. MIDDLETON
McMaster University, Hamilton, Ontario

ABSTRACT

Zones of breccia within the Madison Group of southwest Montana consist of very poorly sorted angular fragments of calcilutite or silty limestone, which are set in a fine grained matrix of crushed "rock-flour" and cemented by calcite. In places where the matrix was silty or sandy it weathers yellow-brown and contains abundant authigenic quartz crystals. The breccias are confined stratigraphically to zones which may be correlated with evaporites in subsurface sections. The upper contacts of the breccia zones are indistinct but the lower contacts are well defined; in some localities, brecciation occurred in place with little displacement of the fragments.

The brecciation resulted from the collapse and crushing of non-soluble strata after the solution by ground water of beds of evaporite.

INTRODUCTION

It has been recognized for some years that extensive breccias found within sedimentary sequences and which are confined to more or less well defined strata or zones may be caused by solution of underlying or interstratified evaporites and collapse of the less soluble beds. Such breccias have been described by Norton (1917) and Reynolds (1928) as "Founder Breccias." As far as the author is aware, however, there are few detailed descriptions of them in the literature and no description of the particular occurrences which are discussed in this paper.

The solution-collapse origin of breccias in the Madison group of Montana was recognized by Sloss (1952), Laudon and Severson (1953), and Nordquist (1953), but Andrichuk (1955) was the first to publish a correlation between subsurface anhydrite and surface breccias in this area. It is clear that the solution-collapse theory was current before 1950, but it was not widely accepted until more recently (Hadley, 1950; Denson and Morrisley, 1954).

In the Mississippian of western Canada the solution-collapse origin of breccias has been recognized by Douglas (1953) in the Mount Head Formation and by Stearn (1956) in the Shunda Formation. Breccias of similar origin are known to be present in the Devonian of Alberta and Manitoba. They have also been briefly described from the Silurian of the Michigan basin by Landes (1948).

[1] Manuscript received April 14, 1960.

DESCRIPTION

Extensive breccias in the Madison Group of southwestern Montana have been noted by several authors. Andrichuk (1955) has pointed out that the breccias are rarely encountered in subsurface but that the zones which contain breccias at surface outcrops may be correlated with bands of anhydrite in the adjacent subsurface. The base of the Charles Formation has been defined by some workers as the base of the lowest thick anhydrite bed. However, since it became obvious that anhydrite was deposited much earlier in some areas than in others, there has been a tendency to reject this definition of the base of the Charles and to include at least some of the anhydrites in the Mission Canyon Formation. In this paper the entire Madison succession above the Lodgepole Formation is assigned to the Mission Canyon Formation. Figure 1 shows the Madison succession in the Bridger Range, as measured by Laudon and Severson (1953).

Several zones of breccia are present near the top of the Madison in southwestern Montana. One, which may be over 100 feet thick, is easily recognizable at many different surface sections (the "main" breccia of fig. 1), while others both above and (rarely) below this zone are less easily correlated

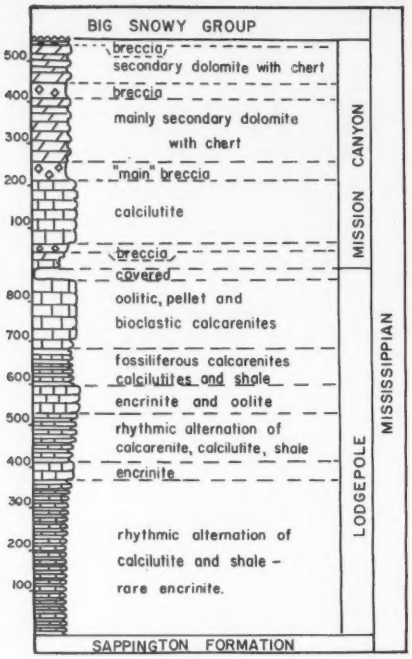


FIG. 1.—Stratigraphic section, Madison Group, Fairy Lake, Bridger Range, Montana. Simplified from Laudon and Severson, (1953).

between different sections. The description given in this paper is based on examination of breccias from all Madison zones exposed in the Limestone Hills, in the Smith River area of the Belt Mountains, and in the Bridger Range.

In the sections examined, the "main" breccia overlies a zone more than 100 ft thick of dense "birdseye" calcilutite, which may also have some interbedded dolomite. The calcilutite zone forms a topographic feature, above which the breccias are usually poorly exposed. Some of the best exposures may be seen in the Bridger section described by Laudon and Severson (1953). This section is somewhat unusual for the area, however, inasmuch as there is an abundance of secondary dolomite at the top of the Madison which is not found in most of the other sections which were examined.

The size of fragments in the breccias varies from those which are too small to be seen with the naked eye to those which are so large that they are not readily recognizable as fragments; one block of limestone in a breccia in the Limestone Hills is more than 10 ft long. The fragments are characteristically very angular and irregular, blocky or tabular in shape; some fragments, however, do show a slight rounding of the edges.

By far the most abundant rock type in all the breccias studied is a lithographic or sublithographic limestone (calcilutite). Thin sections show that many of these fragments have been slightly recrystallized. Another common type is an ochre-yellow weathering calcareous siltstone or fine grained sandstone which grades into a silty or sandy limestone. Lamination is common in the siltstone or fine sandstone. Calcarenites are not common, and fossiliferous fragments are rare. Fossiliferous fragments have been found, however; for example, silicified *Lithostrotion* was found in the "main" breccia in the Bridger Range. Chert fragments are found in small quantities in many of the breccias. Dolomite fragments are very rare except in sections such as that in the Bridger Range where there has been extensive secondary dolomitization.

Careful examination revealed that fragments of breccia are themselves common within the breccia proper; this indicates more than one phase of brecciation. The breccia within the fragment is very similar to the breccia in which the fragment occurs, and it is thought to have a similar origin (see fig. 2, and discussion below).

The fragments in a breccia, or within a certain zone in a breccia, may be all of one lithology, but in some cases the breccias are definitely polymictic (that is, several lithologic types are found as fragments). It is clear that in the thicker breccias there has been a considerable mixing of fragments from several different strata. Nevertheless, in the thicker breccias a rude "stratigraphy" can frequently be distinguished because specific rock types are abundant at certain zones within the breccia and rare or absent at other zones. The matrix type also varies from zone to zone or irregularly within the breccia.

The top of breccia zones are frequently not sharply defined; brecciation may extend

much higher stratigraphically in some places than in others within the same section. A gradual transition may take place upwards from a breccia consisting of mixed, rotated fragments into one in which there is demonstrably little movement of the fragments and the rock has been brecciated in place.

The lower boundary of almost every breccia is well defined. The only exceptions to this rule were seen in the Limestone Hills, where the beds are almost vertical. This observation confirms that in this instance the solution of the evaporites which led to collapse and brecciation took place after the main diastrophism. In vertical beds it is clear that evaporite solution will be equally effective in causing collapse of beds which are stratigraphically above and below the removed evaporite.

Brecciation in place is common. At first glance the rock may not appear to be brecciated at all, but the brecciation may be revealed by the presence of an irregular line of broken chert lenses. More careful examination shows that the rock itself is brecciated, with lithographic limestone fragments set in a matrix which is primarily only slightly coarser than the fragments. The lack of contrast between fragments and matrix makes such breccias easy to overlook in the field.

Several different types of cement or matrix are found. In decreasing order of abundance they are as follows:

1.—Slightly silty, ochre-weathering, very fine crystalline calcite. At first sight this (and the other very fine crystalline matrix type described below) may appear to be a primary (that is, sedimentary) matrix. The true origin is revealed by thin sections, which show that such a matrix is composed of very finely crushed rock cemented by very finely crystalline calcite (fig. 2). Both this yellow- or reddish-weathering matrix and the similar weathering silty limestone fragments may contain abundant authigenic quartz crystals or secondarily enlarged clastic quartz particles. It is thought that the authigenic crystals were formed by redistribution during cementation of quartz which was originally present as fine terrigenous silt particles. Large authigenic quartz crystals of the type described are never found in the pure calcilutite fragments nor in the corresponding pure finely crystalline calcite matrix or cement.

2.—Dark gray, very finely crystalline calcite. This is characteristic of those breccias in which most of the fragments are of pure limestone. It is particularly characteristic of brecciation in place, as described above.

3.—Coarsely crystalline sparry calcite. This type of cement, which is the normal cavity filling type ("granular cement" of Bathurst, 1958), is rather rare in the breccias.

Some breccias contain layers of coarsely crystalline, comb-structured, calcite tufa. It could not be determined whether or not these are related only to the present erosion surface. Limestone fragments in breccias associated with these tufa zones commonly have been recrystallized and bleached to an ochre or cream color.

The general characteristics of the breccias may be summarized as follows:

1.—Different breccia zones may be from a few inches to more than 100 ft thick. The breccias are commonly more or less continuously developed within one stratigraphic interval.

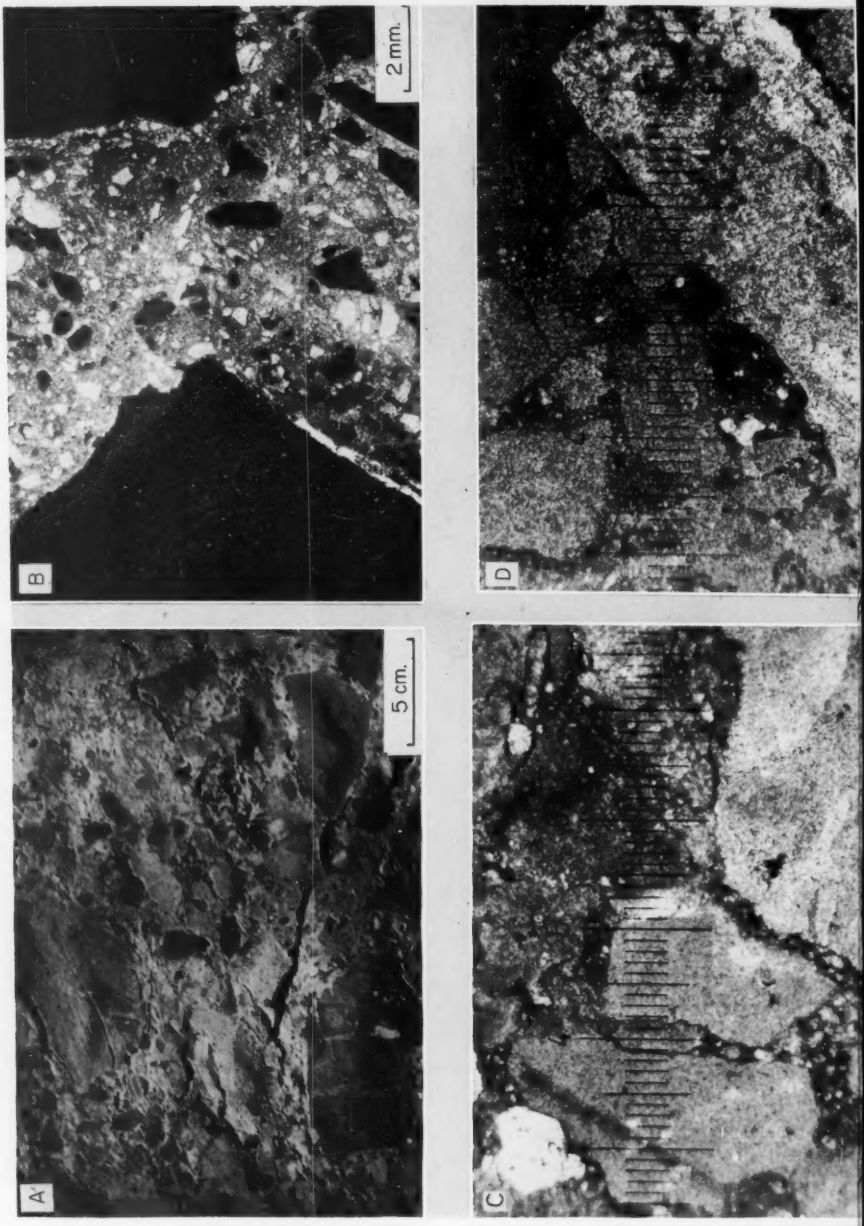
2.—The breccias commonly occur in surface exposures. Occurrences in subsurface are known, but are not common. It can be shown that the surface breccias correlate with evaporites in subsurface.

3.—The fragments in the breccias are highly angular to subangular and are very rarely rounded; the sorting is very poor and the range of sizes great, the average size ranging from approximately 1 to more than 50 cm; the fabric is chaotic.

4.—The breccias are oligomict, rarely polymict. The fragments are commonly of lithographic to sublithographic limestones, silty ochre-weathering limestones, and chert. Dolomite and fossiliferous limestone fragments are rare.

5.—The bottom contact of a breccia zone is sharp, but the upper contact is not. Breccias may grade up from polymict and chaotic, to oligomict or in place breccias. Locally, brecciation may extend higher stratigraphically in some places than in others, but the base of any breccia zone remains at the same stratigraphic position.

6.—The breccias may have a very fine


A
5 cm.
B
2 mm.
C
D

matrix which is difficult to distinguish from the fragments or the matrix may be impure ochre- or reddish-weathering very fine calcite with abundant authigenic quartz. Sparry calcite cement is rare.

It is thought that these general characteristics exclude all theories of origin other than that of solution-collapse. It should be noted that these remarks apply only to the particular breccias described in this paper. In other areas (for instance, in the Mississippian of Moose Mountain, Alberta; Illing, 1959, p. 51) breccias of different origin are found closely associated with solution-collapse breccias. It is not thought, however, that any of the breccias which are described in this paper could have been formed penecontemporaneously or by metasomatic replacement or by recrystallization.

Whereas the breccias described in this paper were formed by solution-collapse, it does not follow that their date of origin is recent. It is well known that subsurface evaporites may dissolve in circulating ground waters at distances of several miles from the actual outcrop (for instance, the Devonian Prairie Evaporite in Saskatchewan: Tomkins, 1955). It is therefore possible that some collapse took place during erosion in post-Madison, pre-Big Snowy, or pre-Amsden times. No real evidence was discovered which would either support or refute this hypothesis. The fact that fragments of breccia were found within the breccias is not considered to be significant. Solution, collapse, and cementation are undoubtably slow and continuous processes, so that breccias formed during an early collapse might be cemented and then rebrecciated during a later phase of the same main period of solution brecciation.

FIG. 2.—A.—Exposure of breccia approximately 200 feet below top of Madison, Limestone Hills, Montana. The fragments at this locality consists of calcilutite and calcareous siltstone; the matrix is very fine grained, limonitic calcite, with authigenic quartz (see B & C).

B.—Same locality as A: a photomicrograph of a breccia contained as a fragment within the breccia proper. Calcilutite fragments are set in a fine grained calcite matrix with abundant large crystals of authigenic quartz full of inclusions.

C.—Same locality as A: a fragment of breccia may be seen in the lower right corner of the photomicrograph; other fragments are calcilutite. The matrix is fine grained limonitic calcite with two large crystals of authigenic quartz visible near the upper left corner of the photomicrograph (9 scale units = 5 mm).

D.—Lowest breccia, Fairy Lake section, Bridger Range. The rectangular fragment in the lower right corner of the photomicrograph is a fragment of silty limestone; the other fragments are of calcilutite. The matrix is fine grained calcite and contains a few small quartz crystals (9 scale units = 5 mm).

DISCUSSION

It might be expected that in a breccia produced by solution-collapse the interstices between the fragments would be filled not by a fine grained matrix but by a sparry cement. Thin sections of the matrix show clearly that this type of cement is not well developed because during brecciation a large quantity of very fine fragments, or rock flour, was produced. This fine material partly filled the cavities and provided abundant nuclei for the growth of crystalline cement which was deposited from ground water, thus preventing the growth of large crystals.

There are three possible reasons why such a large quantity of rock flour was formed during brecciation: (1), it may be that a large quantity of fine materials was formed by the simple process of brecciation and mechanical crushing of the fragments as solution and collapse took place; (2), brecciation might be in part a result of the volume shrinkage consequent upon the conversion of primary gypsum to anhydrite owing to increase in temperature and pressure during diagenesis (Macdonald, 1953); (3), the brecciation might be in part a result of the reverse process—that is, hydration and swelling of anhydrite during the early stages of solution. Udden (1924) described a breccia formed in this way which consisted of angular fragments of limestone in a gypsum cement. A similar breccia was described by Trechemann (1913), who confirmed that such a breccia has a high content of rock-flour by dissolving the gypsum in water and examining the residue.

In any breccia which is formed by mechanical crushing, and presumably also in breccias formed by the processes outlined above, it may be expected that the

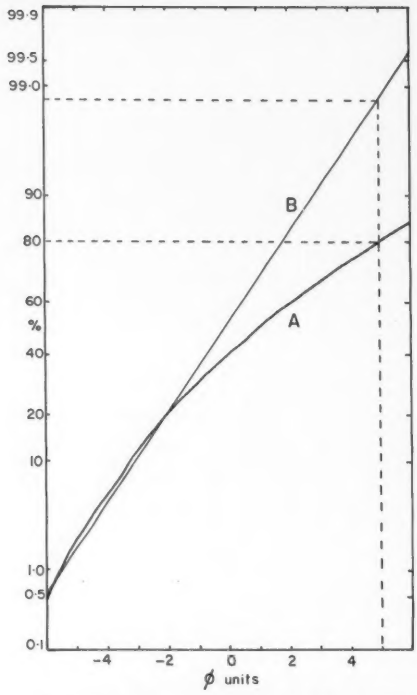


FIG. 3.—A plot of a log-normal distribution (B) and a Rosin's distribution (A) on log-probability paper (for discussion see text).

size distribution will follow Rosin's Law rather than the normal or log-normal distribution (Pettijohn, 1957, p. 41). Unfortunately, since it is not possible to disaggregate the breccias described in this paper, it was not possible to check this supposition. A comparison between the Rosin's distribution and the log-normal distribution is provided by figure 3, which shows a Rosin's distribution (line A) plotted on log-probability paper. A log-normal distribution would plot on this paper as a straight line. If a log-normal distribution is plotted which has much the same size distribution as the coarser part of the given Rosin's distribution (line B on fig. 3), it is clear that it will contain much less fine material than the Rosin's distribution. Thus, in the example shown the Rosin's distribution contains 20 percent by weight in the size range $<\frac{1}{16}$ mm, whereas the log-normal distribution contains only about $1\frac{1}{2}$ percent in this size range. This consideration may help to explain why there appears to be so much fine material in the breccias. Although it was not possible to confirm quantitatively that the breccias have a Rosin's distribution, comparison of the illustrations of the breccias (fig. 2) with illustrations of known Rosin's distributions, such as tillites, does show some resemblance.

One further factor which may contribute to the formation of extensive solution breccias is the interbedding of thin beds of limestone with evaporites. It appears to be possible to remove a very thick section of pure, highly soluble evaporites without very extensive brecciation of the overlying beds; at any rate without the formation of a breccia such as is described in this paper. Such appears to have been the case in the outcrop of the Devonian in Manitoba. Probably several hundred feet of Prairie evaporite have been removed, yet Baillie (1950) records relatively little brecciation of the overlying beds. For this reason the author believes that a thick breccia usually indicates an original zone of thin interbeds or interlaminations of limestone and anhydrite.

ACKNOWLEDGEMENTS

Thanks are due to L. V. Illing and R. V. Best for criticism and discussion and to P. Hansen for able assistance in the field.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 31, NO. 2, PP. 196–214
FIGS. 1–17, JUNE, 1961

DISTINGUISHING BETWEEN BEACH AND DUNE SANDS[1]

FRANCIS P. SHEPARD AND RUTH YOUNG
Scripps Institution of Oceanography, University of California, La Jolla, California

ABSTRACT

The comparison of adjacent pairs of beach (largely foreshore) and dune sands from 74 localities of world-wide distribution has shown that it is generally possible to distinguish between the two, particularly if there are predominant onshore winds. The dune sands are usually rounder than the adjacent beach sands, have a larger silt content, and this silt has a higher content of heavy minerals. The beach foreshores, on the other hand, usually contain more shells and other calcareous organisms than the dunes. There is also some reason to believe that mica content is greater in beach foreshores than in adjacent dunes. The sand of beach berms appears to be intermediate in most respects between that of the foreshores and dunes.

The areas where beaches and dunes are most difficult to distinguish are those where there are longshore, extremely variable, or offshore winds. In such localities it is thought that the dune sands are blown back onto the beaches causing intermixture and that in some cases the dunes are derived from sources other than from the adjacent beach. The best results in separating the two environments have come from beaches of the west coast of the United States and Baja California where onshore winds predominate.

It is suggested that the chief reason for the differences between dune and beach sands is that the wind picks up from the beaches more of the rounder grains than of the flat and angular grains. There is no reason to believe that the grains are rounded appreciably by the wind in transit to the dunes. Nor does there appear to be any evidence from these comparisons that the dune grains become frosted. The greater quantity of heavy minerals in the dune silt fraction may be caused by removal by the wind of the light minerals.

INTRODUCTION

Distinguishing ancient beach and dune sands may serve to tell the direction and approximate position of the shore line in a stratigraphic sequence. Beaches and dunes are often buried and hence incorporated into a stratigraphic sequence by prograding coastal fans which build over the dunes without destroying them, whereas an encroaching seashore may destroy the dunes as the waves act at higher and higher levels. Beaches and dunes also may be incorporated into the stratigraphic column during subsidence, provided the beaches and the dunes inside grow upward apace with the coastal subsidence. Where bedding is present beaches and dunes can often be distinguished by the distinctive nature of the cross-bedding in the dunes. Many dune sands, however, lack this distinctive cross-bedding so that other criteria become necessary to distinguish them from bordering beaches. Among these criteria roundness has been referred to by a number of investigators as being greater in dune sands than in the beach from which the dune was derived (MacCarthy, 1935; Russell, 1939; Pettijohn, 1956, and Beal and Shepard, 1956).

Other investigators have questioned the authenticity of any actual difference in roundness between beaches and dunes (Mattox, 1955; Mason and Folk, 1958). Furthermore, a trip along the length of Padre Island, Texas, with the collection of beach and dune pairs at approximately 2-mile intervals, yielded samples which, when investigated by the present writers, showed a number of beach sands that were rounder than the adjacent dune sands. Accordingly, material was collected from a considerable number of other localities from various parts of the world, largely by the senior writer, and these have been subjected to tests.

[1] Acknowledgments: This work represents one of the results of research carried out under Contract Nonr-2216(01), Office of Naval Research. The writers wish to acknowledge the assistance which they received from M. A. Beal, G. V. Cohee, J. T. Enright, R. L. Folk, P. K. Hansen, D. L. Inman, R. R. Lankford, J. R. Moriarty, F. B Phleger, Tj. H. van Andel, and J. D. Waskom. Manuscript received April 25, 1960.

If the dune sands are more rounded than beach sands because of the abrasion between grains produced during wind transportation, as is a common impression, very little rounding would have occurred in transporting sand to the bordering dunes. That being the case it would be necessary to collect samples at considerable distances within the dunes in order to get appreciable differences from the parent beach sand. If, on the other hand, the principal difference comes from the sorting action of the wind in picking up rounder grains from the beach, an immediate difference should be found and a comparison be made by collecting dune sands at close propinquity to the beach where the parentage is more certain. The experiments of MacCarthy and Huddle (1938) indicated the importance of wind as a selector of round grains. As further indication, the comparison of sand dunes at varying distances from the beach (Beal and Shepard, 1956) showed that there was no progressive change at least over a distance of several miles, and studies by the present writers have given more confirming information. Furthermore, wind-blown sand collected from a wheel track across a beach was found to have as great a difference in roundness from the beach sand as was found in samples taken well within the adjacent dunes. Therefore, no hesitation was felt in comparing the nearby dune sands with those of the beach. In general, the dune samples were obtained on the windward slope well above the highest level reached by waves. In order to determine whether the roundness change occurred between foreshore and berm or between berm and dune, a considerable number of berm samples were compared with both dune and foreshore sands.

Suggestions have been made that beaches and dunes may be distinguished by their grain size parameters, particularly the sorting, skewness, and kurtosis (Mason and Folk, 1958). These factors have been checked between beach and dune samples in the present study from a large number of localities. Finally, the general composition of beach and dune constituents has been given some comparative study, and an attempt has been made to look for a difference between the frosting of grains of the beaches and the adjacent dunes.

ROUNDNESS ("PRIVOTABILITY") STUDIES

Methods and Purpose

There is a large volume of literature on the methods of determining roundness and sphericity. Roundness according to Wadell (1932) is the ratio of average radius of curvature of the several corners or edges of a solid to the radius of curvature of the maximum inscribed sphere, whereas sphericity is the degree in which the shape of a fragment approaches the form of a sphere. Realizing the great difficulty of measuring the diameters of sand grains along more than two axes, most methods have tested roundness of grain outline. Wadell, for example, compared the average radius of the corners and edges to the radius of the maximum inscribed circle. Krumbein (1941) used values determined by Wadell to set up a visual comparison chart based entirely on silhouettes. A well-constructed globe or ball represents a perfect sphere, if all diameters are equal, whereas (using the outline method) a coin may have the highest degree of roundness but very low sphericity. The scale developed by Powers (1953) is also based on Wadell's values, but it shows photographs of models which give the eye a sense of the third dimension. The "sphericity" method of Riley (1941) gives the ratio between inscribed and circumscribed circles on grain outlines and differs from the others in that it may give high values to grains of low sphericity and roundness as, for example, a 6-sided flake of mica.

In choosing a method for determining roundness or sphericity it is necessary to consider the purpose of the comparison. In the present study this purpose was not so much to determine the amount of wear which grains had undergone by long distance transportation, which as shown by Kuenen (1958, 1960) and Russell (1939) may or may not result in sphericity and roundness, but to distinguish the difference in shape of grains at or near the boundary between beaches and dunes that could be produced by selective choice of grains by the wind. If such selection takes place, there should be a means of determining the boundary between ancient dunes and beaches which lie contiguous to each other. It is evident that well-rounded grains can roll

and, hence, be blown more easily than grains with flat surfaces and, furthermore, that grains with projecting points are more difficult to dislodge from a beach surface and are, therefore, somewhat less likely to be carried by the wind into the dune. On the other hand, thin platy grains like mica are more easily transported than spherical grains once they have been dislodged. Thus, there are two factors working against each other, making it necessary to find out from observations of many beaches and dunes the shape differences which actually exist.

To compare dune and beach roundness a somewhat modified version of Powers' scale was adopted by the writers. In this scale the idea of "pivotability" was given paramount importance so that the grains which could be most easily pivoted were given the highest values. Examples of typical grains in the six roundness grades used are shown in figure 1.

Technique Employed

In all cases in the present investigation beach sands were compared with those of adjacent dunes. To do this the samples were sieved and a split was taken from the same size for each pair. In most cases the .062 to .125 mm grade was used largely because this is usually present in beach and dune sands and constitutes a large proportion of the beaches and dunes of the Gulf of Mexico and the west coast of the United States where most of the samples for the work were collected.

The split was obtained by spreading the sample on a large tray and taking portions at random with a scoop. This was found from tests to be fully as representative of the entire sample as the split obtained by a much more time-consuming sample splitter.

The split was then spread on a gridded tray and examined under the binocular-microscope. Grains were chosen by following a grid pattern on the tray so as to avoid bias. A count of 100 grains was made and the types were recorded on a *Denominator* (a blood-cell counter) which stops at 100 and can be manipulated with one hand while the other hand moves the tray and adjusts the microscope. After a little practice, no trouble is found in using this counter by the touch system so that the eyes do not have to be moved from the microscope. Average time for a count appears to be about 10 minutes.

Results of such counts are made much more reliable when the operator is unaware of the nature of the sample being tested. Otherwise a certain bias can be introduced. At first, the present authors tested only one pair at a time, but it was found that it was difficult to avoid some bias if the second sample examined appeared on first sight to be either rounder or more angular than the other. As a result, six or more unknown samples were counted before using a check list to see what they represented. In this way no bias can be developed. Another important thing is to have more than one operator. This increases the number of grains examined and thus helps avoid the possibility of a chance spread of the roundest or the most angular grains on the tray which may develop occasionally in a count of 100. Furthermore, if one operator is having an off day or a temporary tendency to make the classes too high or too low it will show up in a striking difference between the counts of the two operators. Where such large differences existed, both operators repeated the counts again as unknowns, with almost always a satisfactory adjustment.

Only two operators were involved in this study, both of whom have become quite experienced in studying roundness during a period of more than two years, in which time each has measured more than 60,000 grains. This experience has resulted in a high degree of consistency in each operator's measurements.

Results of Roundness Counts

The result of examination by both writers of 74 pairs of beach and dune samples from many parts of the world is indicated in table 1 and in figure 2. At first sight it will be seen that there is by no means a consistent difference between the roundness of the beach sand and that of the adjacent dune, as had been indicated by the previous counts made on a much smaller group of pairs by Beal (Beal and Shepard, 1956). On the other hand, the dune sands are generally more round, and the averaging of a large number of samples from a locality showed a greater degree of roundness in almost all cases.

The most striking conclusion from the

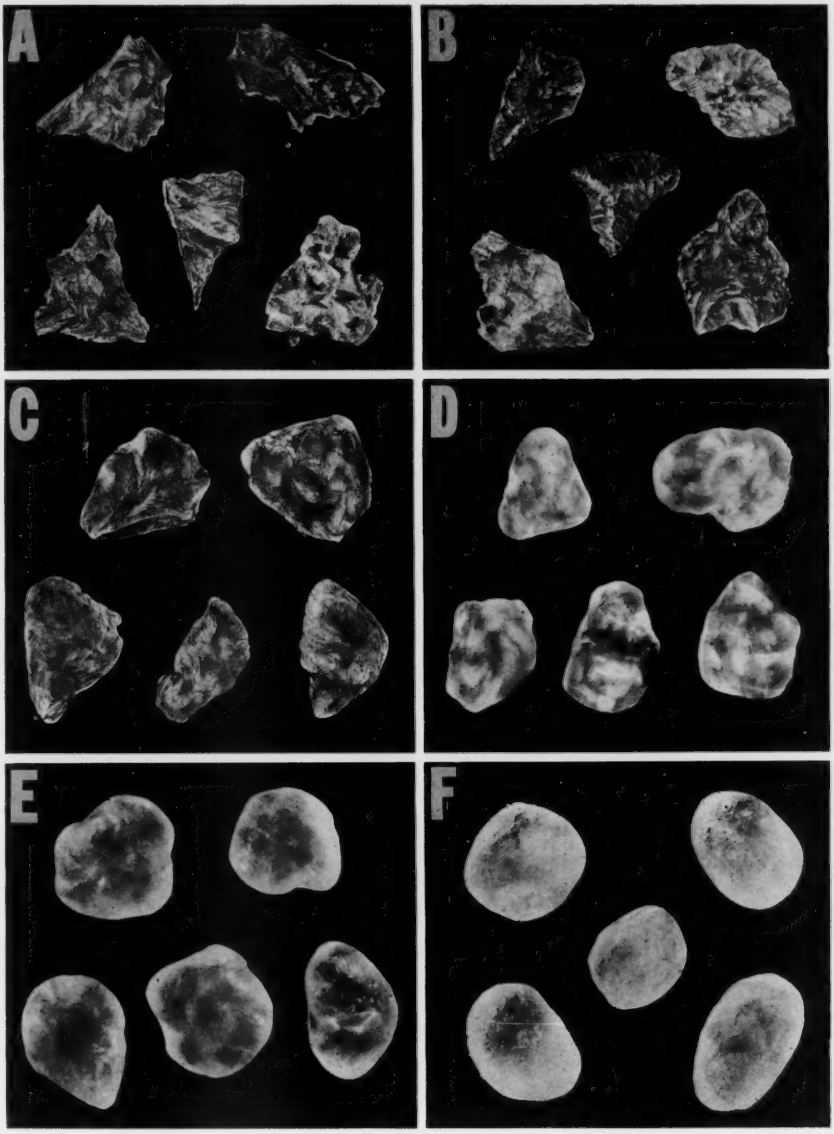

FIG. 1.—Examples of the six classes used for roundness (pivotability) determinations. Modified after Powers (1953). A = Very angular, B = Angular, C = Sub-angular, D = Sub-rounded, E = Rounded, F = Well-rounded. Photographs by junior author, retouching by J. R. Moriarty.

TABLE 1

Sample Location	Roundness		Percent Silt Content		Percent Black Minerals in Silt		Percent Crystals* in Silt		Percent Shells in .25 — .5 mm.		Mean Diameter, M_ϕ		Sorting, σ_ϕ		Skewness, $\alpha_{2\phi}$		Kurtosis, β_ϕ	
	Beach	Dune	Beach	Dune	Beach	Dune	Beach	Dune	Beach	Dune	Beach	Dune	Beach	Dune	Beach	Dune	Beach	Dune
ONSHORE WINDS (27 prs.)																		
U. S. West Coast (15)																		
La Push, Wash.	25.82	29.15	.02	.19	—	—	—	—	—	—	2.02	1.96	.44	.44	−.55	−.80	.73	1.07
Copalis, Wash	27.27	30.06	.04	.16	8	50	2	10	—	—	2.81	2.84	.25	.23	−.52	−.44	.64	.61
Westport, Wash.	28.84	29.56	.02	.03	4	4	—	—	—	—	2.71	2.48	.23	.37	−.57	−.43	.78	.57
Bay City, Wash	25.47	28.15	.14	.03	1	12	0	1	—	—	2.77	2.73	.23	.20	−.52	−.30	.57	.70
Coos Bay, Oregon	26.49	26.75	.02	.03	tr	2	0	1	—	—	2.27	2.54	.31	.29	−.19	−.28	.50	.59
Cresent City, Calif.	27.78	39.06	.03	.01	tr	18	0	2	20	4	2.77	2.43	.26	.29	−.54	−.28	.81	.62
Eureka, Calif.	29.94	31.20	.01	.03	6	13	—	—	—	—	2.14	2.18	.27	.29	−.15	−.21	.63	.66
Bodago, Calif.	29.73	30.17	.04	.10	3	5	—	—	3	tr	2.69	2.50	.30	.32	−.77	−.50	.93	.59
Moss Landing, Calif.	29.06	30.02	.02	.01	tr	1	0	2	—	—	1.96	2.17	.37	.34	−.35	−.35	.65	.68
Morro Bay, Calif.	31.06	34.23	.02	.18	2	20	0	4	5	2	2.56	2.74	.28	.24	−1.04	−.04	1.46	.58
Pismo Beach, Calif.	29.92	31.73	.20	.68	40	50	50	70	—	—	—	—	—	—	—	—	—	—
La Jolla, #1, Calif.	25.97	26.92	.03	.06	—	—	—	—	—	—	2.66	2.54	.28	.26	+.04	−.19	.71	.62
La Jolla, #2, Calif.	26.34	26.33	.03	.03	30	60	10	70	10	1	2.71	2.51	.28	.25	−.07	−.20	.57	.72
La Jolla, #3, Calif.	26.28	26.48	.04	.04	40	45	8	8	12	16	2.47	2.48	.29	.26	−.17	−.35	.62	.88
Coronado, Calif.	27.56	28.08	.22	.09	55	60	2	20	3	tr	2.81	2.38	.34	.32	−.12	−.41	.62	.69
Baja Calif. West Coast (5)																		
Rosarita Beach	24.56	27.71	.04	.11	3	25	tr	15	—	—	2.41	2.44	.22	.25	−.14	−.20	.73	.68
La Mission	25.79	28.69	.03	.12	10	23	tr	8	—	—	2.41	2.54	.27	.24	−.37	−.25	.63	.79
Ensenada #1	22.46	25.61	.03	.11	0	8	0	1	tr	2	0.99	2.78	.72	.26	−.32	−.46	.42	.54
Ensenada #2	23.41	26.76	.02	.08	1	12	0	1	1	0	0.96	2.72	.52	.30	0	−.50	.58	.77
Scammons	26.67	30.40	.03	.05	1	50	0	8	35	10	2.41	2.83	.45	.22	−.73	−.36	.80	.68
Miscellaneous (7)																		
Puerto Rico #1	25.99	26.84	—	—	—	—	—	—	59	16	3.19	2.29	.40	.47	−.08	−.62	.58	1.04
Puerto Rico #2	27.05	30.15	—	—	—	—	—	—	30	14	2.28	2.33	.45	.51	−.31	−.24	.69	.59
Puerto Rico #3	28.40	27.76	—	—	—	—	—	—	12	10	0.92	1.71	.81	.37	−.30	−.14	.69	.76
Fano, Denmark	32.26	33.47	.05	.09	6	6	5	1	5	2	2.88	2.76	.34	.38	−.38	−.42	.79	.68
Skallingen, Denmark	29.81	32.43	.05	.01	5	3	2	1	7	tr	2.46	2.59	.46	.28	−.39	−.11	.76	.57
Sagami Bay, Japan	26.30	27.40	.02	.23	14	10	—	—	—	—	2.26	1.88	.44	.67	−.48	−.72	.68	.82
Eboshi, Japan	25.63	29.24	.12	.24	22	15	—	—	—	—	2.36	1.87	.41	.59	−.88	−.42	1.05	.61
OTHER (not onshore) (47)																		
Padre Island (27)																		
M-101	30.67	33.66	.13	.18	15	25	2	10	4	16	3.15	3.12	.31	.35	−.61	−.37	1.00	.69
M-103	33.03	34.07	.04	.15	21	31	3	25	9	7	2.92	3.05	.29	.28	−.24	−.79	.79	.86
M-106	31.30	33.57	.08	.03	30	24	18	13	2	11	2.69	2.89	.35	.27	−.37	−.22	.74	.78
M-107	31.25	30.26	.04	.08	17	27½	6	9	6	16	2.97	3.05	.31	.29	−.48	−.45	.90	.90
P-8	33.72	34.62	.08	.15	19	25	5	26	8	4	—	—	—	—	—	—	—	—
P-10	30.84	32.30	.02	.07	10	20	5	18	2	0	2.96	3.02	.33	.29	−.18	−.38	.64	.79
P-13	32.03	33.65	.12	.13	14	25	5	16	1	tr	2.99	3.19	.27	.23	−.41	−.48	.74	.91
P-14	34.22	34.61	.07	.06	15	30	9	27	—	—	3.06	2.97	.25	.26	−.48	−.31	.80	.69
P-16	34.73	35.08	.09	.06	10	30	—	—	—	—	3.03	3.16	.27	.19	−.33	−.32	.74	1.05

TABLE 1—*Continued*

Sample Location	Roundness		Percent Silt Content		Percent Black Minerals in Silt		Percent Crystals* in Silt		Percent Shells in .25 – .5 mm.		Mean Diameter, M_ϕ		Sorting, σ_ϕ		Skewness, $\alpha_{3\phi}$		Kurtosis, β_ϕ	
	Beach	Dune	Beach	Dune	Beach	Dune	Beach	Dune	Beach	Dune	Beach	Dune	Beach	Dune	Beach	Dune	Beach	Dune
P-18	30.31	34.20	.03	.05	25	35	7	11	2½	2	2.98	2.89	.25	.25	−.18	−.40	.84	.76
P-20	32.25	33.70	.04	.07	8	25	5	10	10	1	3.03	3.03	.27	.29	−.26	−.20	.78	.72
P-22	29.76	32.82	.04	.05	8	15	8	19	34	15	2.79	2.83	.35	.36	−.83	−1.08	.83	1.36
P-25	33.25	32.39	.04	.07	12	8	1	4	tr	5	2.84	2.96	.33	.29	−.79	−.83	.85	1.17
P-27	34.14	32.63	.03	.07	2	5	3	14	14	43	2.70	2.58	.42	.66	−.50	−.91	.62	.64
P-30	32.54	34.50	.01	.03	2	4	0	5	18	4	2.75	2.86	.39	.29	−.64	−.24	.74	.55
P-32	33.57	35.23	.02	.02	2	1	2	12	20	15	2.34	2.48	.59	.35	−2.30	−.14	1.09	.63
P-33	33.63	33.22	tr	tr	—	—	—	—	9	1	2.58	2.51	.39	.34	−.46	−.12	.87	.65
P-35	33.74	34.19	.02	.06	20	28	2	21	4	2	2.81	2.96	.33	.30	−.12	−.33	.58	.80
P-37	33.59	32.06	.02	.04	10	45	15	8	1	5	2.77	2.73	.33	.36	−.09	−.17	.61	.61
P-39	32.90	32.33	tr	.05	—	—	—	—	12	4	2.49	2.80	.34	.23	−.35	−.13	.79	.74
P-42	33.90	32.37	.02	.01	25	32	5	19	tr	3	2.77	2.61	.29	.27	−.10	−.04	.59	.63
P-45	31.65	33.04	.03	.03	2	18	2	3	2	4	2.54	2.62	.28	.31	−.14	−.13	.64	.71
P-48	33.65	35.86	.02	.04	3	15	0	7	3	½	2.58	2.62	.31	.27	−.10	−.07	.81	.74
P-50	35.17	32.32	.10	.07	7	10	—	—	2	4	2.74	2.66	.23	.30	−.39	−.10	.83	.67
P-53	33.89	33.82	.02	.03	13	29	7	7	0	2	2.69	2.65	.25	.28	−.12	−.04	.56	.57
P-57	35.94	35.93	.15	.09	65	38	—	—	3	6	2.68	2.57	.21	.23	−.24	−.17	.76	.61
RG-4	31.73	32.92	—	—	—	—	—	—	1	8	—	—	—	—	—	—	—	—
Miscellaneous (20)																		
Kiel, Germany	34.93	31.95	.02	2.16	4	0	0	0	—	—	2.19	2.00	.31	.29	−.45	+.03	.97	1.04
Lake Geneva	29.69	27.10	.45	7.08	12	0	0	0	5	tr	2.73	2.36	.51	.44	−.33	—	.75	—
Dhahran, Sandi Arabia	39.16	36.89	.03	.14	3	tr	0	0	—	—	1.36	2.60	.41	.48	−.81	−.13	.72	.50
Karachi, Pakistan	21.59	24.99	1.49	2.80	2	1	0	1	½	2	3.18	3.43	.31	.35	+.10	−.14	.87	.66
Kalutara, Ceylon	27.81	31.31	.34	.34	30	10	11	3	—	—	2.38	1.49	.30	.64	+.07	−.67	.80	.67
Hambantota, Ceylon	26.91	26.17	.16	.04	35	10	6	0	½	tr	1.65	1.90	.79	.33	−.73	−.45	.66	1.27
Colombo, Ceylon	30.72	31.75	.20	.64	55	70	5	20	10	8	2.49	2.30	.41	.55	−.34	−.31	.61	.58
Galle, Ceylon	32.28	31.69	.04	.01	1	15	0	0	60	60	1.57	2.25	.63	.33	−.29	−.45	.49	.70
Waltair, India	32.01	29.70	.82	.03	70	25	3	tr	1	tr	2.80	1.95	.38	.49	−.24	−.39	.71	.69
Kakinada, India	31.14	29.34	.60	1.21	20	65	2	3	—	—	2.82	2.88	.37	.36	0	−.11	.70	.89
Seven Pagodas, India	34.85	30.96	.03	.03	20	8	8	tr	—	—	1.94	1.83	.39	.52	−.49	−1.04	.82	1.23
Thai #1	37.38	32.27	.02	.03	tr	tr	4	1	1	0	2.49	2.34	.31	.26	−.90	−.58	.97	.81
Thai #2	35.33	37.72	.03	.03	tr	tr	1	6	—	—	2.26	2.51	.32	.25	−.22	−.36	.56	.76
Okudi, Japan #1	29.21	28.56	.01	.03	1	3	0	0	16	12	1.35	1.36	.33	.35	−.61	−.46	.76	.49
Okudi, Japan #2	28.60	30.10	.12	.60	30	20	0	0	52	49	2.36	2.52	.42	.34	−.36	−.21	.67	.79
Oiso, Japan #1	23.95	27.03	.05	.11	18	34	0	0	—	—	2.01	1.85	.61	.52	−1.18	−.56	1.33	.75
Oiso, Japan, #2	25.18	27.73	.01	.02	17	17	0	0	—	—	1.54	1.43	.65	.71	−.42	−.08	.83	.42
San Felipe, Baja California	29.25	30.32	.01	.90	1	3	tr	2	—	—	0.82	1.28	.78	.75	+.13	+.17	.46	.99
Magdalena Bay	29.25	29.85	.38	.36	40	61	11	9	12	tr	2.67	2.59	.27	.39	−.19	−.23	.74	.59
Las Cabras, Baja California	24.12	23.00	.02	.04	8	16	tr	3	—	—	1.48	1.74	.60	.46	−.25	−.41	.55	.76

* Probably all zircon.

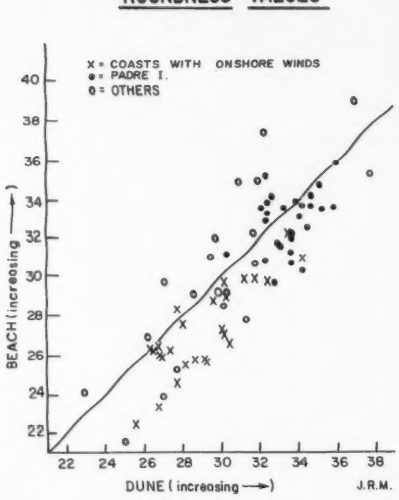

FIG. 2.—Comparison between roundness values of beach (foreshore) and dune pairs. All those above have rounder beach sands. Virtually all of the pairs from coasts with onshore winds have rounder dune sands, whereas there is little difference along other coasts. Scales are those of Powers (1953) times 100.

study has come from comparing the differences in areas where the prevailing winds are onshore with those where the winds are either longshore, variable, or ordinarily offshore. It was found that all but two samples of the former show greater dune roundness and one of the two showed a tie-count. Along the Texas coast the wind is ordinarily from the southeast and hence onshore. Therefore, the samples studied by Beal showed consistently greater roundness in the dunes. As the result of a trip made by G. A. Rusnak and the senior writer along Padre Island, 27 pairs of beach and dune sands were compared. These showed 17 with rounder dune sands, 1 tie, and 9 with rounder beach sands. This seemed to be out of line with the results obtained by Beal which came partly from the same island. Two factors probably contributed to the difference. One was that the more extensive suite of samples from Padre Island was collected during and shortly after a strong northwest wind had changed conditions from those of onshore to offshore winds; during much of this trip the sands were being blown onto the beach by the wind coming from the dunes (fig. 3). The other factor may be that the southern and central portion of Padre Island, where almost all of the rounder beach sands were found, has a beach which is largely a mass of shells without much terrigenous sand available. Although terrigenous sand was collected from the beach, it may not be representative of the sand which formed the dunes.

Many of the other exceptions to the rounder dune sands came from India, Ceylon, and Thailand. In these areas the monsoons cause alternate onshore and offshore winds. Similarly, an attempt to identify samples of the sands collected by Waskom (1958) from northwest Florida produced poor results, but rounder dune sands were found in the only line which extended in from a beach with onshore winds. Where the wind was either longshore or offshore, no difference was found.

On the other hand, numerous samples taken all along the west coast of the United States and in adjacent Baja California where the winds are almost entirely onshore showed remarkably consistent results, with the dunes rounder than the beaches.

Roundness and Grain Size

The best possible results of roundness studies should come from testing the roundness of the various grain sizes produced by sieving the sample. This, however, is very time-consuming, so that it was only done with a few selected samples. Taking 11 of the sample pairs from the west coast, all of which showed greater dune roundness than beach in the .062–.125 mm size, the roundness was also measured on both dune and beach samples taken from sievings having size limits of .125–.177 mm, .177–.25 mm, and .25–.5 mm. A plot of the results shows that the roundness varies irregularly with size in both dunes and beaches (fig. 4). Only four samples showed a progressive change. In the others the roundness alternately increased and decreased. Comparison of roundness in the pairs shows that five of the samples had greater roundness in all sizes of the dune sand. Only the largest size, .25–.5 mm, showed no difference between dunes

FIG. 3.—A photograph taken through jeep windshield during the collection of beach and dune pairs from Padre Island. The strong offshore wind is indicated by the streaks of sand moving diagonally seaward.

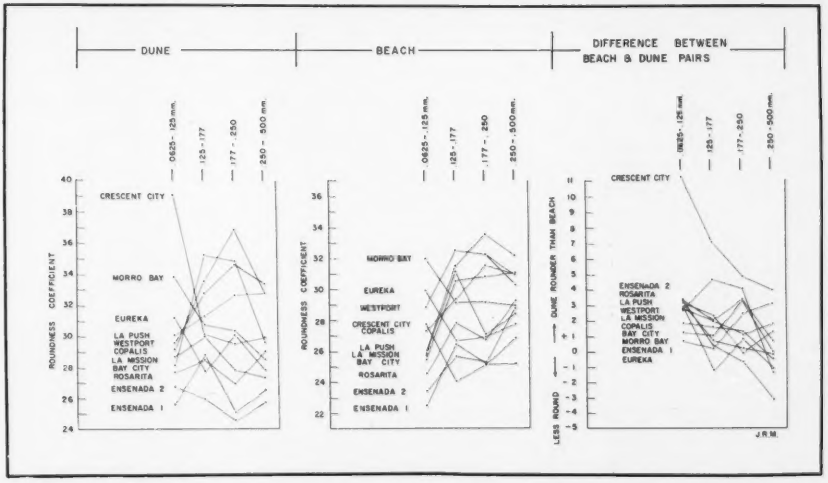

FIG. 4.—Showing the variation in roundness coefficient with grain size in a series of dune and beach (foreshore) sands from the west coast of North America. The difference between the beach and dune pairs in relation to grain size is indicated on the right.

and beaches. A few comparisons from other areas have also indicated that there is little consistent difference in the results obtained by using different grain sizes.

An attempt was made to try larger grain sizes for roundness comparisons in several of the samples from Padre Island where the .062 to .125 size did not show greater roundness in the dunes. No significant difference was found so that it appeared that the roundness was not a function of size in these cases.

Roundness in Sandstones

In order to compare the roundness values obtained in the study of beaches and dunes with those in some of the sandstones which have been described as unusually round, samples of sandstones from a number of formations said to have very round grains were obtained (through arrangements made by G. V. Cohee). Those from which the grains were easily separated included St. Peter Sandstone, Jordan Sandstone, Bromide Formation, Hickory Sandstone, Bidahochi Formation, and Carrizo Sandstone. From all of these, roundness was determined in two or more size grades. No trouble was found in making the roundness test of the coarser sizes, but the .062–.125 size proved somewhat difficult because of possible confusion of the original grains with quartz cement and incipient crystal growth along with what appeared to be artificially broken fragments. Neglecting these fine grains, the results show clearly that all but one of these sandstones have higher roundness values than those obtained in the dunes and beaches (table 2). The somewhat doubtful determination of roundness in the .062–.125 sizes shows much less contrast but indicates that even in the finest sizes these sandstones are probably rounder than typical beaches and dunes of the present day. A few samples of sands from Georges Bank off the New England coast and a sample from a turbidity current deposit in a submarine canyon outside Georges Bank are the only modern sediments tested by the writers with roundness comparable to the round-grained sandstones.

TABLE 2.—*Roundness values of sandstones*

	.062–.125 mm	.35–.71 mm	.71–2.0 mm
St. Peter Sandstone	45.87	57.46	68.40
Jordan Sandstone	47.77	59.12	72.17
Bromide Formation	39.65	71.24	78.84
Hickory Sandstone	34.09	54.12	61.19
Bidahochi Formation	39.77	49.04	67.45
Carrizo Sand	36.73	34.89	37.50

The sandstone samples also differed from the beach and dune sands in showing a decided decrease in roundness with decrease in size, as has been said to be the case for sand and sandstones in general (Pettijohn, 1956, p. 60–65).

Foreshore and Berm Roundness

Virtually all beach sands for the tests were collected from foreshores. Therefore, in order to determine whether the difference between the beach sands and the dunes might not actually be a difference between foreshore and berm (inner horizontal portion of a beach), a series of sample pairs were taken from these two environments and roundness tests were run, using the same methods. All 20 of the sample-pairs which were examined in this way were taken from areas where there were onshore winds and hence where the dune sands were rounder. The results are remarkably consistent. Eighty percent of the berms (fig. 5A) have rounder sand than that on the foreshores. Comparison of the berm and dune (where present) in the same areas shows that the roundness values in the berms are in general intermediate between those of the foreshore beach and the dune (fig. 5B).

Two possible explanations exist for greater roundness in the berm than on the foreshore. One is that the waves carrying the sand up onto the berm may select the rounder grains. The other is that the occasional offshore winds mix the dune sand in with the sand on the berm, whereas the active wave action on the foreshore inhibits such a mixing. Worthwhile experiments could be conducted with artificial beaches in wave tanks. These should help explain the difference.

DIFFERENCES IN SIZE PARAMETERS

Mean Diameter

One might anticipate that wind blowing over a beach would pick up the smaller grains and hence that a dune sand could be easily distinguished from a parent beach by

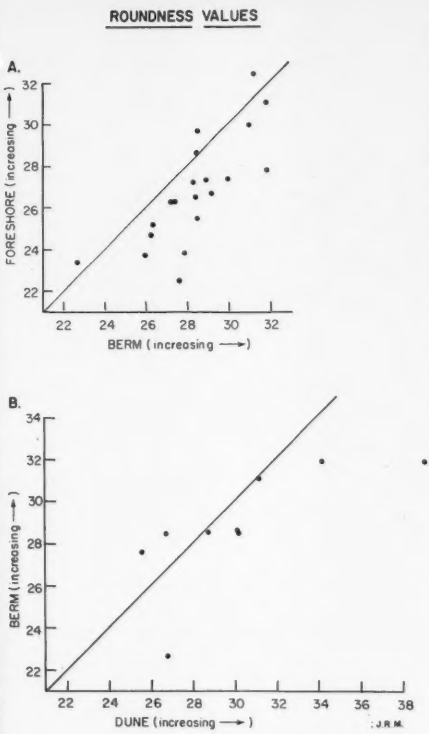

FIG. 5. A.—Comparison between roundness values of sample pairs taken from the foreshore and the adjacent berm (backshore). (Powers' scale times 100). B.—Comparison between roundness values of sample pairs taken from the berm and adjacent dune. (Powers' scale times 100.)

its smaller grain size. The exchange, however, is not as simple as that. In the first place, the beach is already well sorted and the wind is evidently capable of picking the larger grains almost as well as the smaller, since the shape of the grain appears to make more difference than the slight range in size. Furthermore, the smaller grains are carried farther and may entirely by-pass the dune, and after deposition the dune sand, being dry, is subject to more sorting from the wind than the relatively wet beach. This sorting may remove the finer grains.

A test of grain size may be made to best advantage by mean diameters, that is, the average of the 16th and 84th percentiles (Inman, 1952). The mean seems preferable to the median (the 50 percentile) because it gives a more representative measure of the average size of particles in the frequency distribution and is not merely the mid-point of the size distribution. Comparison of the mean diameters of each pair of beach-dune samples (fig. 6) shows that there is little difference between the two. In these comparisons, 48 are within 0.2 phi of each other; of the others, 14 show coarser beach sands and 9 coarser dune sands. Furthermore, no difference exists in the cases of onshore wind beaches from the others. From these results, therefore, it would appear that the mean diameters do not constitute a reliable means of distinguishing beach and dune sands.

Silt Content

All of the beach and dune sands were analyzed for silt and clay content. Actually, clay is a minor factor and the greater part of the fines proved to be relatively coarse silt. A comparison between the silt content of the beach and dune pairs has shown a strik-

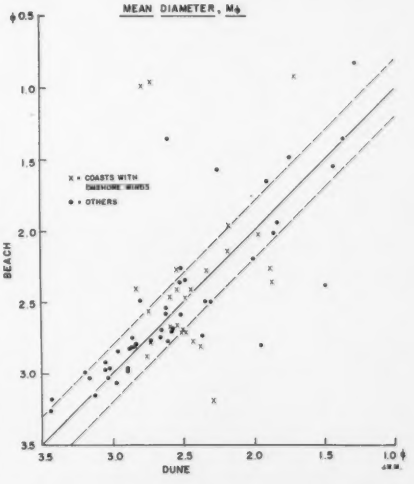

FIG. 6.—Comparison of mean diameter of pairs of beach (foreshore) and adjacent dune sands. The dashed lines are located within 0.2 ϕ of the line which indicates the same value for the pair.

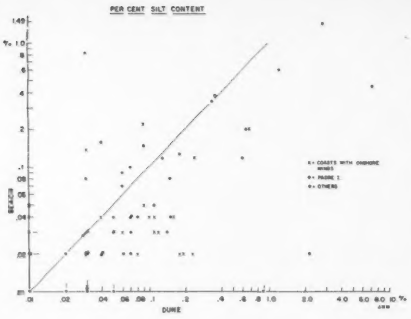

FIG. 7.—Comparison of the percent of silt for each of the beach-dune pairs. Note that here, as in the case of roundness, the coasts with onshore winds have considerably more silt in the dunes than in the beach foreshores.

ing contrast (table 1, fig. 7). Sixty-seven percent of the pairs have a higher silt content in the dune sands. Little, if any, relationship exists with wind direction since beaches with onshore winds have 71 percent with higher silt.

Comparison of the silt content between foreshore and berms shows more silt in 58 percent of the berms (fig. 8). Here also the dunes show more silt than the berms.

The explanation of the greater silt content in the dunes than beaches appears to be relatively simple. Wave action is much more likely to prevent deposition of fine sediments than wind action, because the waves are almost always sufficiently turbulent to keep silt in suspension whereas the wind is much more variable. On the berms the waves have less continuous effect than on the foreshore so that silt introduced by wind can settle on the sand between the occasional periods of wave inundation.

Sorting, Skewness, and Kurtosis

Studies of beaches and dunes from a single locality have suggested that other size parameters such as sorting, skewness, and kurtosis can serve to distinguish the two (Mason and Folk, 1958). In order to test these parameters more widely, cumulative curves were made from all of our size analyses using a combination of sieving and settling tube. From these curves sorting, skewness, and kurtosis were obtained using the formulas suggested by Inman (1952). The values of sorting, skewness, and kurtosis based on 25 and 75 percentiles used by some other investigators are statistically less representative as pointed out by Inman so that they were not used. The more comprehensive formulas used by Folk and Ward (1957) were applied to a few samples for comparative purposes, but as the results differed so slightly from those obtained using the simpler Inman formulas, the latter were used throughout.

Sorting (phi deviation) is here expressed as $\sigma_\phi = \frac{1}{2}\ (\phi_{84} - \phi_{16})$. Using this formula to compare the sorting of the beach and dune pairs it was found that there are only minor differences in the sorting of the pairs (fig. 9). Seventy-three percent of the pairs had a sorting value within 0.1_ϕ of each other. Little or no difference existed between areas with onshore winds and the others. These differences are only slightly favorable to better dune sorting and, therefore, while this agrees with the opinion of Mason and Folk (1958) for Mustang Island, Texas, it does not appear to offer a valid means for distinguishing dune and beach sands.

Skewness (second phi skewness), which measures the symmetry of the curve and particularly the distribution in the tails of the curve, is here expressed as

$$\alpha 2_\phi = \frac{1/2(\phi 5 + \phi 95) - Md\phi}{\sigma_\phi}.$$

The skewness values we obtained appear to

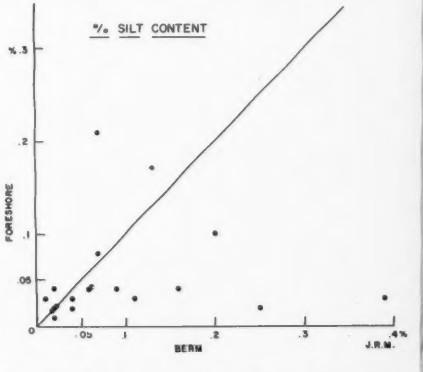

FIG. 8.—Showing comparison of the silt content between pairs of foreshore and berm samples.

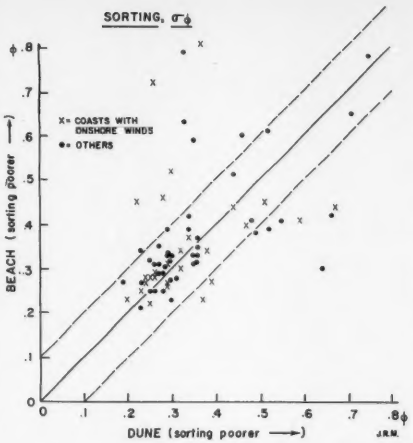

FIG. 9.—Comparing the sorting of the pairs of beach (foreshore) and dune sands. The dashed lines indicate a difference of 0.1ϕ from the condition of equal sorting for the pair.

be more negative than is entirely normal. This may be caused by the effect of the settling tube method as compared to that of sieves, but it affects the analysis of both beaches and dunes in the same manner so that a comparison is justified. Despite the fact that silt values are higher in dunes which tends to produce positive skewness, the difference in the skewness of dunes and beaches is very slight with 53 percent having a skewness value within 0.2ϕ of the paired sample (fig. 10). Where the wind was onshore, only 46 percent of the samples showed the dunes with more positive skewness whereas 59 percent of the others had the dunes skewed more to the positive. This last may have some significance, but it is not evident to the writers. Here again the findings of Mason and Folk (1958) for Mustang Island indicating more positive skewness in dunes are favored by such a scant margin that the criterion as a means of distinguishing beaches and dunes does not appear to be practical.

The expression of kurtosis has not been used extensively by sedimentologists, but it has been suggested by Mason and Folk (1958) as offering some promise in differentiation of dunes and beaches particularly when skewness is plotted against kurtosis. Phi kurtosis, which measures peakedness of the curve by comparing sorting in the central portion with the average spread in the tails of the distribution, is here expressed as

$$\beta_\phi = \frac{1/2(\phi 95 - \phi 5) - \sigma_\phi}{\sigma_\phi}.$$

Plotting the difference in kurtosis between beach and adjacent dune (fig. 11) again shows that there is no trend in this parameter which will allow distinction between beaches and dunes. The comparison shows that 66 percent had values within 0.2ϕ of each other. Plotting the skewness against the kurtosis for all of the dunes and beaches (fig. 12) also fails to show any significant trend which would differentiate the two environments.

Comparisons between mean diameter and sorting and between sorting and skewness for all beach and dune samples were attempted (figs. 13 and 14). These again failed to show any striking difference between the environments. Thus, it appears that differentiation of dunes and beaches by size parameters other than silt content is not possible.

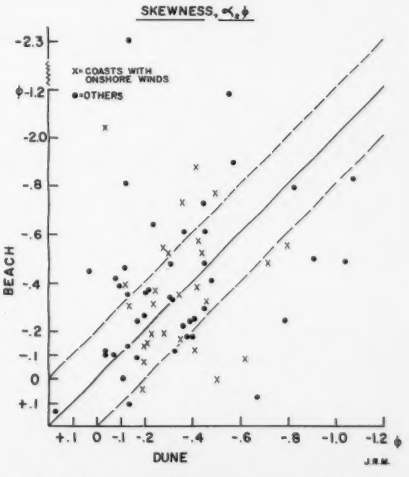

FIG. 10.—Comparing the skewness of the pairs of beach (foreshore) and dune sands. The dashed lines indicate a difference of 0.2ϕ from the condition of equal skewness for the pair.

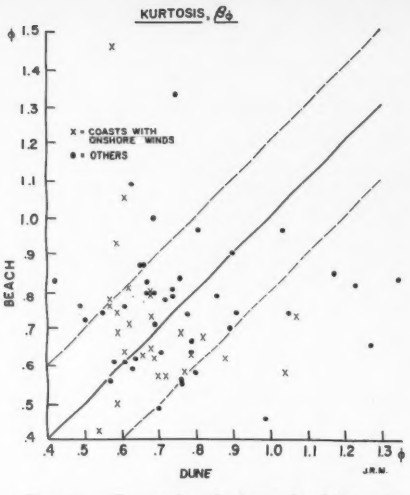

FIG. 11.—Comparing the kurtosis of the pairs of beach (foreshore) and dune sands. The dashed lines indicate a difference of 0.2ϕ from the condition of equal kurtosis for the pair.

DISTINCTION BY CONSTITUENT COMPOSITION

Black Minerals in the Silt Size

Investigations by Bradley (1957, p. 116), Stewart (1956), and von Englehardt (1940) have shown that heavy minerals in the .062–.125 mm size are more common in dunes than in beaches respectively on Mustang Island, at San Miguel Lagoon along the coast of Baja California, and on parts of the German coast. In studying the composition of the .062–.125 mm fraction of a considerable number of beach and dune samples along the Gulf Coast and the California coast the senior writer did not find any appreciable difference in the black minerals, the most easily identified heavies. It was observed, however, that these heavies are greatly concentrated in the coarse silt fraction. Accordingly, a check was made of the silt size fractions of all the beach and dune pairs used for the present study. Here a striking difference was found. Using the simplest test, which was counting the percentage of black minerals (omitting biotite which is very different from the others from a sedimentation viewpoint), it was found that the silt from 45 dunes had more black minerals than that of the corresponding beaches whereas 16 beaches had more than the dunes, and 3 were ties (table 1). Thus, this agrees in general with the findings of Bradley, Stewart, and von Englehardt. It will be seen from figure 15 that many of these differences are very considerable, amounting to as much as 50 times as many black minerals in one dune. The percentages of black minerals are surprisingly large, particularly since the samples were not collected from areas where an obvious concentration had taken place, such as in the black mineral lag concentrate left after the light minerals of a beach or dune have been largely removed.

The composition of the black minerals in four of the samples was determined by Tj. H. van Andel and found to be predominantly ilmenite and magnetite with some hornblende. It is thought that these minerals are also dominant in most other samples.

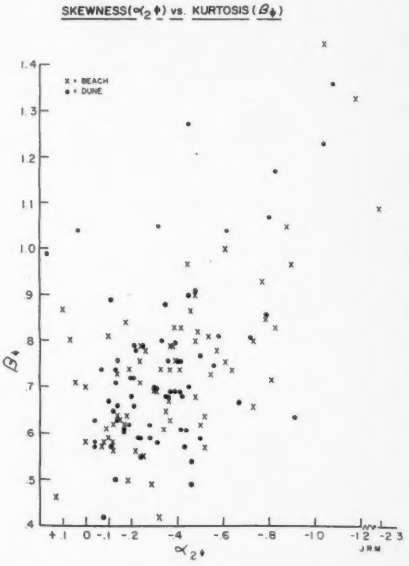

FIG. 12.—Comparison of skewness against kurtosis for individual samples of beach (foreshore) and dune sands. There is little difference between the two environments.

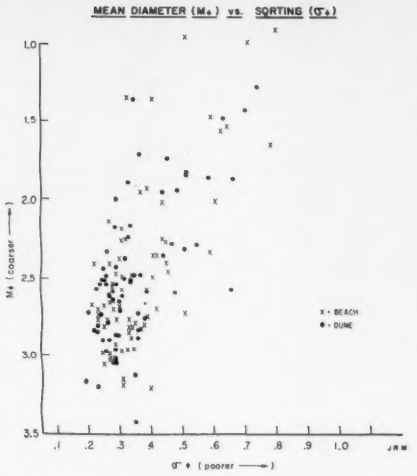

FIG. 13.—Comparison of mean diameter against sorting for individual samples of beach (foreshore) and dune sands. There is little difference between the two environments.

The most interesting discovery was that in the samples from the west coast of the United States and Baja California where the dunes showed a consistently greater roundness, the dunes had an equally consistent excess of black minerals of silt size. All but one west coast dune showed more black minerals than the corresponding beach, and this one had approximately the same number. The Mustang-Padre Island area in southern Texas where roundness was not particularly effective in distinguishing beaches and dunes proved to have 20 samples of silt with more black minerals in the dunes as compared to 4 with more in the beaches. On the other hand, the samples from Asia showed more black minerals in the beaches than in the dunes. Since most of the Asiatic beaches are located in zones lacking consistent onshore winds, the failure of the rule here may perhaps be related to the back and forth movement of the black minerals because of alternating onshore and offshore winds.

The explanation of greater content of black minerals in the silts of dunes than in the silts of beaches is not clearly evident. It is possible that the rather high degree of rounding shown in most of the black minerals, where the contrast was striking, may explain the greater concentration, provided that winds are more capable of picking up round grains. The greater weight of the heavy black minerals would not make as much difference in the case of silt size frac-

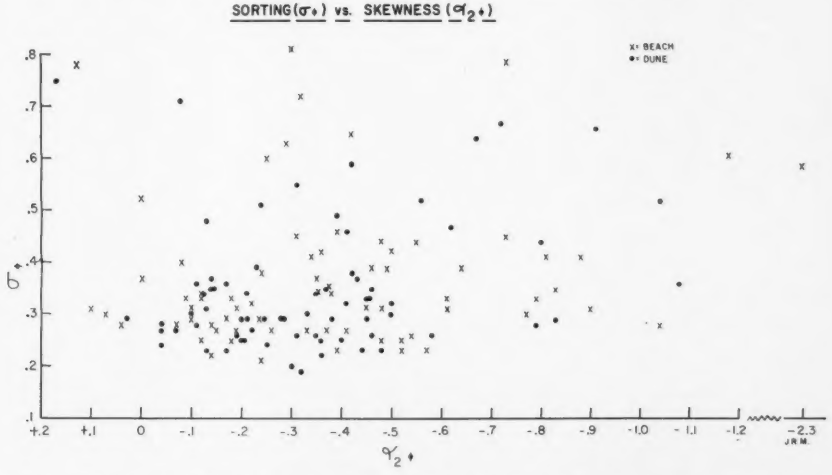

FIG. 14.—Comparison of sorting against skewness for individual samples of beach (foreshore) and dune sands. Again there is little difference between the two environments.

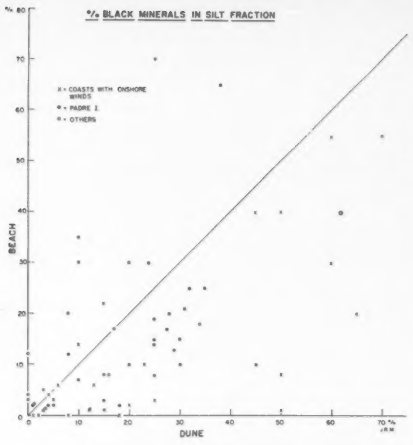

FIG. 15.—Comparison of black mineral percentages in the silt fraction of the beach (foreshore) and dune pairs. The higher content of black minerals in the dunes along coasts with onshore winds and on Padre Island is indicated.

tions as in coarser material. However, a few cases where black minerals were found in the .25 to .5 mm fractions indicated the same trend, although the number of occurrences and the amounts of black minerals were such that the case is not well established. Another possibility is that the black minerals represent the lag concentrate due to wind working over the dunes more than the foreshores of the beaches where wetness prevents much wind action. In this reworking the light mineral fraction of silt size may be largely removed.

Zircon Crystals in the Silt Sizes

In comparing the silt fractions of the dunes and beaches it was observed that crystals were surprisingly abundant although they are rare in the sand sizes. Examination of these crystals in a few samples by Tj. H. van Andel showed that they were all zircons and hence a heavy mineral. Van Andel found that an approximately equal number of zircons lacked crystal form or showed much abraded crystals. Since it is far easier to identify the crystals under binoculars than the other zircons, these were used as a test for environment. It is assumed that the crystals in the other samples are also zircon as they are all similar in appearance under the binoculars. Tabulation showed that the zircon crystals, like the black minerals, were also more abundant in the dunes than in the beaches (table 1 and fig. 16). The samples with abundant zircon crystals were almost entirely samples which also had a high content of black minerals.

Since the crystals have decidedly more rounding than the rest of the minerals, it can be suggested that their greater concentration in the dunes is caused by the selectivity of the wind. As in the case of the black minerals, a lag concentration is also possible.

Shells and Other Calcareous Fragments

No complete study has been made of the organisms found in the beach-dune pairs. Estimates of organisms were made, however, of the .25–.5 mm fraction in all of the pairs. Beaches would be expected to have more shells, since few shell animals live on the dunes and numerous shells are cast up on the beaches by the waves. Although the

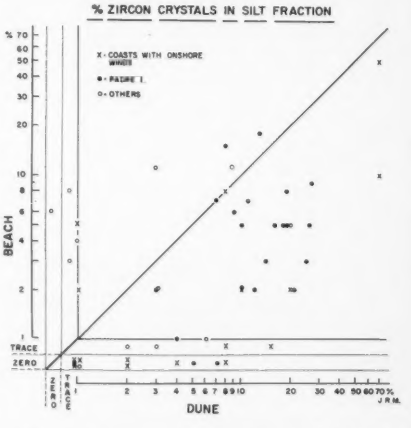

FIG. 16.—Comparing percentages of zircon (or similar appearing) crystals in the silt fractions of the beach (foreshore) and dune pairs. Included are cases where no crystals or only a trace of zircon crystals were found in one member of the pair. Here also the dune samples have more crystals than the beach foreshores on the coasts with onshore winds and on Padre Island.

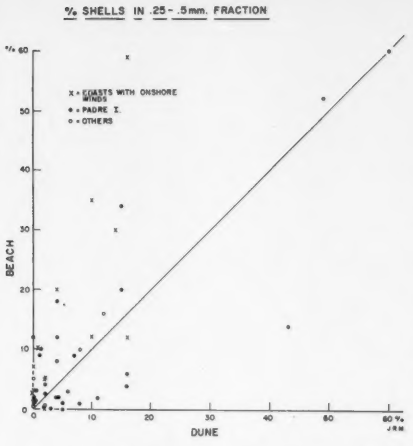

FIG. 17.—Comparison of percentages of shells in the .25–.5 mm fraction in the paired beach (foreshore) and dune samples. Here a greater quantity of shells is found in the beaches except on Padre Island where they are virtually the same in both environments.

wind does transport shells, they are usually larger than the sand grains and more angular so that they are not quite as easily picked up by the wind as the sand. Furthermore, the shells are more likely to be leached out of the dunes. The comparisons showed that 67 percent of the beach sands had more shells than the dune sands (table 1, fig. 17). The test worked well for onshore wind coasts, with 86 percent having more shells in the beach, and almost equally well for the other areas except Padre Island. In some cases the shell content in dunes may have been introduced by man because kitchen middens are quite common among coastal dunes. The sizes studied, however, should minimize the effect of man since small fragments are not commonly left by man although the shells might have been reduced in size by nature subsequent to man's activities.

Perhaps the most surprising thing about the shells is the large number of beaches which did not appear to have any shells at all. This scarcity was even discovered in many of the tropical beaches of India and Ceylon.

Foraminifera are very common in some tropical beaches, particularly in tropical islands. They were rare in most of the beaches investigated and even less common in the dunes. At Karachi, however, they constitute 15 percent in the .25–.5 mm size beach material but are scarce in the dunes. In some other beaches rounded calcareous grains probably represent eroded Foraminifera.

Other Constituents

Not many beaches or dunes were found to contain an appreciable content of mica although Karachi is predominantly a mica beach with about one half as much mica in the dunes. The comparison of 28 pairs containing mica showed that mica is more abundant in 17 beaches than in the adjacent dunes whereas 9 show more mica in the dune and 2 were ties. Here again there is some indication that the flat grains in contrast to the round are less subject to wind selection. Furthermore, once the flat mica grains are picked up by the wind they are transported grester distances, in many cases by-passing the dunes.

Plant fibers are found occasionally in beaches and dunes although most of the samples examined had only negligible quantities. In those pairs containing appreciable amounts, plant fibers were more abundant in seven dunes and in only one beach. Presumably the plant fibers come from the vegetation which partly covers many dunes. Plants are rare on beaches although driftwood is locally very abundant, for example in northwestern United States.

GRAIN FROSTING

The common statement that dune sands are more frosted than beach sands may be true, but frosting appeared to be very rare in the dunes bordering the beaches which we investigated. The frosting of sand grains by the wind is considered by Ph. H. Kuenen (1960) to be nonexistent. His experiments showed that frosting was a development of chemical action on the dunes rather than sand blast, although sand blast is well known to frost window panes and pieces of glass left on a beach. The coastal dunes are remarkably free of frosted grains, and in no

TABLE 3.—*Summaries of the nine tests*

("×" = Onshore)
("●" = Padre Is.)
("○" = Others, not onshore)

		Beach Higher		Tie		Dune Higher		Total No.	Sign Test (probability)
		No.	%	No.	%	No.	%		
Roundness Values (Fig. 2)	×	1	3.7	1	3.7	25	92.6	27	<.01
	●	9	33.3	1	3.7	17	63.0	27	.17
	○	11	55.0	0	0	9	45.0	20	>.25
Total		21	28.4	2	2.7	51	68.9	74	
% Silt Content (Fig. 7)	×	5	20.9	2	8.3	17	70.8	24	.02
	●	6	23.1	3	11.5	17	65.4	26	.03
	○	4	20.0	3	15.0	13	65.0	20	.05
Total		15	21.4	8	11.4	47	67.2	70	
% Black Minerals in Silt (Fig. 15)	×	3	13.6	2	9.1	17	77.3	22	<.01
	●	4	16.7	0	0	20	83.3	24	<.01
	○	9	50.0	1	5.6	8	44.4	18	>.25
Total		16	25.0	3	4.7	45	70.3	64	
% Zircon Crystals in Silt (Fig. 16)	×	2	11.8	1	5.9	14	82.3	17	<.01
	●	2	9.5	1	4.8	18	85.7	21	<.01
	○	6	50.0	0	0	6	50.0	12	>.25
Total		10	20.0	2	4.0	38	76.0	50	
% Shells in .25–.5 mm. size (Fig. 17)	×	12	85.7	0	0	2	14.3	14	.01
	●	13	52.0	0	0	12	48.0	25	>.25
	○	8	80.0	1	10.0	1	10.0	10	.04
Total		33	67.4	1	2.0	15	30.6	49	
Mean Diameter (Fig. 6)	×	13	50.0	0	0	13	50.0	26	>.25
	○	24	53.3	1	2.2	20	44.5	45	>.25
Total		37	52.1	1	1.4	33	46.5	71	
		Beach Poorer		Tie		Dune Poorer			
Sorting (Fig. 9)	×	15	57.7	1	3.8	10	38.5	26	>.25
	○	25	55.6	1	2.2	19	42.2	45	>.25
Total		40	56.3	2	2.8	29	40.9	71	
		Beach more neg.		Tie		Dune more neg.			
Skewness (Fig. 10)	×	12	46.2	1	3.8	13	50.0	26	>.25
	○	26	59.1	0	0	18	40.9	44	>.25
Total		38	54.3	1	1.4	31	44.3	70	
		Beach Higher		Tie		Dune Higher			
Kurtosis (Fig. 11)	×	12	46.2	0	0	14	53.8	26	>.25
	○	21	47.7	2	4.6	21	47.7	44	>.25
Total		33	47.1	2	2.9	35	50.0	70	

case could the difference between a beach and an adjacent dune be determined by degree of frosting.

CONCLUSIONS

Results of Combination of Tests

Comparing the tests for roundness, silt content, black minerals, zircon, and shells for each pair of beach and dune samples, it was found that of the 74 pairs 54 could be identified as having the majority of the tests favorable whereas 14 showed the majority unfavorable and six pairs had the same number of favorable and unfavorable tests. Of the beaches with onshore winds, 25 were favorable and only one unfavorable with one tie. It seems that in areas with onshore wind the tests should prove very reliable in distinguishing between beaches and dunes. Of the Padre Island samples from an area which ordinarily has onshore winds but which had just experienced a strong offshore wind before and during collections, the favorable cases numbered 18 and unfavorable six with three ties. In the northern 44 miles of Padre Island only one unfavorable case was found.

The other areas with offshore or longshore winds proved much less satisfactory, with only 11 favorable and seven opposed along with two ties. Thus it appears that little can be learned from the tests in these areas.

Statistical Significance of the Individual Tests

Table 3 summarizes the results of each of the nine tests. Since the distribution of differences between pairs is conspicuously non-normal, a non-parametric statistical comparison was used. The Sign Test (Dixon and Massey, 1957) indicates that on coasts with onshore winds, beach sand differs from dune sand in five characteristics (roundness, silt content, black minerals, zircon crystals, and shell content). These differences are significant at the .02 level (or less), implying that if there was, in fact, no difference between beach and dune sands in these characteristics, one would observe such a large apparent difference less than two times in a hundred. This is so unlikely that it is concluded that there is a real difference in this group of samples between these two types of sand.

In the Padre Island samples the Sign Test indicated a real difference between environments in three of the tests (silt content, black minerals, and zircon crystals), but not in the other characteristics. Samples from the other areas with offshore or longshore winds proved to differ significantly only in silt content and shell content.

All of the grain size parameter tests proved to be definitely not significant, regardless of area.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 31, NO. 2, PP. 215–230
FIGS. 1–8, JUNE, 1961

CARBONATE SEDIMENTATION ON THE HERON ISLAND REEF, GREAT BARRIER REEF[1]

W. G. H. MAXWELL, R. W. DAY, AND P. J. G. FLEMING
University of Queensland, Brisbane, Australia

ABSTRACT

A survey of the reef flat and sand cay of the Heron Island reef has shown that the bulk of the surface material consists of skeletal detritus derived largely from coral and algae. Oolitic and other accretionary material are absent. The distribution of the skeletal sand is controlled by the faunal, physiographic and current patterns. Several sand facies may be distinguished on the basis of textural and compositional variation, the diagnostic constituents in the different facies frequently being in minor amounts. Granulometric analyses reflect the close relationship between textural variation and such factors as physiography and currents. Grain orientation measurements reflect this same relationship.

INTRODUCTION

Heron Island (latitude 23° 26′ S., longitude 152° E.), situated approximately 44 miles due east of Cape Capricorn, is one of the Capricorn Group which, together with the Bunker Group, forms the southern extremity of the Great Barrier Reef, as shown in the locality map, figure 1. The present work, undertaken in the summer of 1959, was aimed primarily at a detailed study of the nature and distribution of the carbonate sediments on the reef flats immediately surrounding the island.

Eight traverses were run from the island to the reef edge, and bulk as well as orientated samples were taken at 200 foot intervals. The beach and island were sampled in a similar manner, while reconnaissance traverses were made into the lagoon and into the channel beyond the southern reef edge. An approximate zonation of the reef flat, based on topographic factors as well as faunal distribution, was essential for a clear understanding of the sedimentary pattern; this work was carried on simultaneously with the sampling.

Heron Island represents but one of many different kinds of reef development in the Great Barrier Reef Complex; as a consequence, the results of this study do not necessarily reflect the general conditions of sedimentation throughout the complex. It is hoped that further expeditions to other parts of the Great Barrier Reef may eventually provide sufficient information to permit a wider interpretation of the general sedimentary pattern.

[1] Manuscript received May 9, 1960.

PHYSICAL CHARACTER OF HERON ISLAND REEF

Classification

According to Fairbridge (1950, p. 341), the reefs and islands of the Bunker and Capricorn Groups are not of the normal barrier type but resemble the island reefs of the inner platforms. He grouped them in his "Reefs with Islands" type, and following Spender's (1930) subdivision of coral islands, he regarded Heron Island as typical of the vegetated sand cay. The Capricorn and Bunker Groups occupy the southern end of the Great Barrier Reef. They occur inside the 100 fathom line, rising on an average from depths of 15 to 20 fathoms. The Capricorn Channel, up to 50 fathoms deep, separates them from the main outer barrier to the northeast, represented in this region by the Swain Reefs. No outer barrier occurs to the east or southeast. In general, the islands and reefs of the two groups are elongate along E–W or NE–SW axes, with their maximum width near their eastern ends. This type of distribution is quite unlike that found in the outer barrier where the reefs are elongate in a N–S direction, parallel with the line of the barrier margin. The significance of their E–W to NE–SW orientation is not understood, but it is probable that in

FIG. 1.—Location map showing position of Heron Island in relation to other members of the Great Barrier Reef, and to the Queensland coast.

the case of the Capricorn-Bunker Groups, the prevailing southeast winds and the swell from the northwest trending Capricorn channel are mainly responsible for the shaping of the reefs and islands. On the other hand, the reefs of the outer barrier are influenced mainly by the oceanic swell.

Topography, Vegetation and Land Fauna

Heron Island and its parent reef consist of a large tear-shaped reef platform with an east–west axis approximately 7 miles long and a maximum width near its eastern end of approximately 3 miles (fig. 7a). The island proper is a sand cay occupying the western extremity of the platform and is also elongated in an east-west direction. It is 2400 ft long, less than 1000 ft wide and approximately 15 ft above sea level on its southern, windward margin. The island slopes gently northward from the southern scarp and rim to the leeward beach which is less clearly demarcated from the island proper. A mantle of bedded, seaward-dipping beach rock almost completely encloses the island.

Comparatively dense vegetation, mainly of the tree *Pisonia brunoniana*, covers the entire island above the high tide mark. *Causarina* and *Pandanus* are also abundant. The land fauna is dominantly a bird one—the sand burrowing mutton birds (*Puffinus pacificus*) which inhabit the island from September to March, and the higher, tree-living communities of terns (*Anous minutus*). The nesting season for the large turtles (*Chelonia*) during the early summer results in their invasion, particularly of the eastern, lagoonal end of the island, and in the excavation of large nests. As a consequence of the prolonged activity of the turtle and mutton bird, no part of the island's surface escapes disturbance, and many of the textural and structural features which may have been used in the interpretation of the origin of the sandy cay are no longer preserved.

Topographically, the reef province is divisible into four major units: (1) sand cay; (2) reef flat; (3) lagoon; and (4) reef edge.

In this work the main investigation is restricted to the reef flat and sand cay.

The sand cay is the only part of the area permanently above sea level, although large expanses of the reef flat, particularly near the outer margins, are exposed at low tide. The bulk of the sand is found below water level between the patches of coral and algae. No large areas of the reef flat are covered by more than 2 ft of water at low tide, while at high tide depths of more than 8 ft are reached.

Temperature variations on the reef flat have been measured by Endean and others (1956, p. 321–322). The mean temperature rises from 19° C in July (mid-winter) to 26.5° C in January (mid-summer), with ranges during some months of as much as 14° C.

Currents across the reef flat are influenced by the prevailing southeast winds, but they are controlled mainly by topographic factors and tidal movement. The strongest currents flow westward along the southern and northern shores and drain the lagoon and reef flat as the tide recedes. A gentler flow develops in the opposite direction with ad-

vancing tides. Less vigorous currents flow westerly further out on the reef flat and converge near the western tip of the island, where they then enter the deep channel between Heron and Wistari reefs. Other movements over the reef flat are mainly tidal, and because of the shape of the flat, these movements are resolved in approximately north-south directions. As such, the tidal directions tend to be at variance with the general current pattern. Studies of orientated bottom samples reflect these conflicting directions.

PHYSIOGRAPHIC ZONES AND FAUNAL DISTRIBUTION OF THE REEF PROVINCE

Physiography

In addition to the major physiographic units mentioned above, the reef province may be subdivided into smaller zones on the basis of faunal distribution and topographic factors (fig. 2). Detailed faunal zonation has not been attempted in this study as the abundance and diversity of faunas would require the skill of specialists in marine biology. However, broader faunal divisions are evident. These are considered in the latter part of this chapter.

Sand Cay.—Heron Island is a sandy cay rising abruptly from the southern beach to a height of 15 ft and then sloping gently northward. The southern margin is constantly subjected to the strong, prevailing southeast winds which produce ripple marks along the seaward scarp and carry the finer sand upward to form a low marginal ridge. A sandy beach, 50–100 ft wide at low tide, surrounds the island; this in turn is partly surrounded by a belt of beach rock, 30–70 ft wide on the southern shore, 10–20 ft wide in the north and west, and almost completely absent in the east.

Reef Flat.—The reef flat (fig. 7b, d) widens from west to east and is considerably wider beyond the northern shore. It reaches a maximum width of 2500 feet in the south, along the western margin of the lagoon, and more than 4000 ft in the north, also along the lagoonal margin. At low tide, large parts of the flat are above sea level, while no part is covered by more than 3 ft of water. It may be subdivided into four smaller units which are developed to varying degrees on the northern and southern flats.

(1) *Inner Channel or Moat.*—This is most clearly defined along the southern edge of the island where it may be 50 to 100 ft wide and consists of a sandy floored depression 2 to 3 ft below the general level of the reef flat. The moat represents the plunge line of the main body of breaking waves and has resulted initially from wave scour. Its stronger development on the southern flat is caused by the smaller width of the flat and the fact that it is on the windward side. Strong current action has augmented the effect of wave scour. The moat is bordered on its landward side by the beach rock and is the channel through which strong lagoonal currents flow as the tide recedes. These currents enter the moat from the east and southeast.

(2) *Inner Sandy Flat.*—On the southern side the inner sandy flat extends from the moat for a distance of 700 to 800 ft, while it reaches a width of 1200 ft on the northeastern flat and less than 600 ft in the west. It is typified by broad expanses of sand with sparse clumps of living coral and somewhat more abundant dead coral and molluscan debris. The coral population increases progressively seawards. Beche-de-mer are prolific inhabitants of this sandy flat and are responsible for the reworking of the bulk of the surface sediment. Mounds of faecal pellets discharged by these organisms, mainly during the night, are evidence of their activity (fig. 7e). However, because of the lack of mucus or other binding agent, the faecal pellets are rapidly reduced by wave action to mounds of unconsolidated sand.

(3) *Zone of Living Coral.*—This zone merges with the previous zone, the boundary between the two being difficult to define. The zone of living coral contains fewer sand patches and has abundant micro-atolls near its landward side. On the southern flat it extends for 300 to 600 ft but reaches a width of 750 to 1500 ft on the northern flat. In addition to coral, various molluscan communities flourish in this environment.

(4) *Reef Flat Margin or Outer Coral-Algal Zone* (fig. 7c).—Living coral with extensive algal encrustation and sheets of coral shingle are typical of the outer zone. Sand

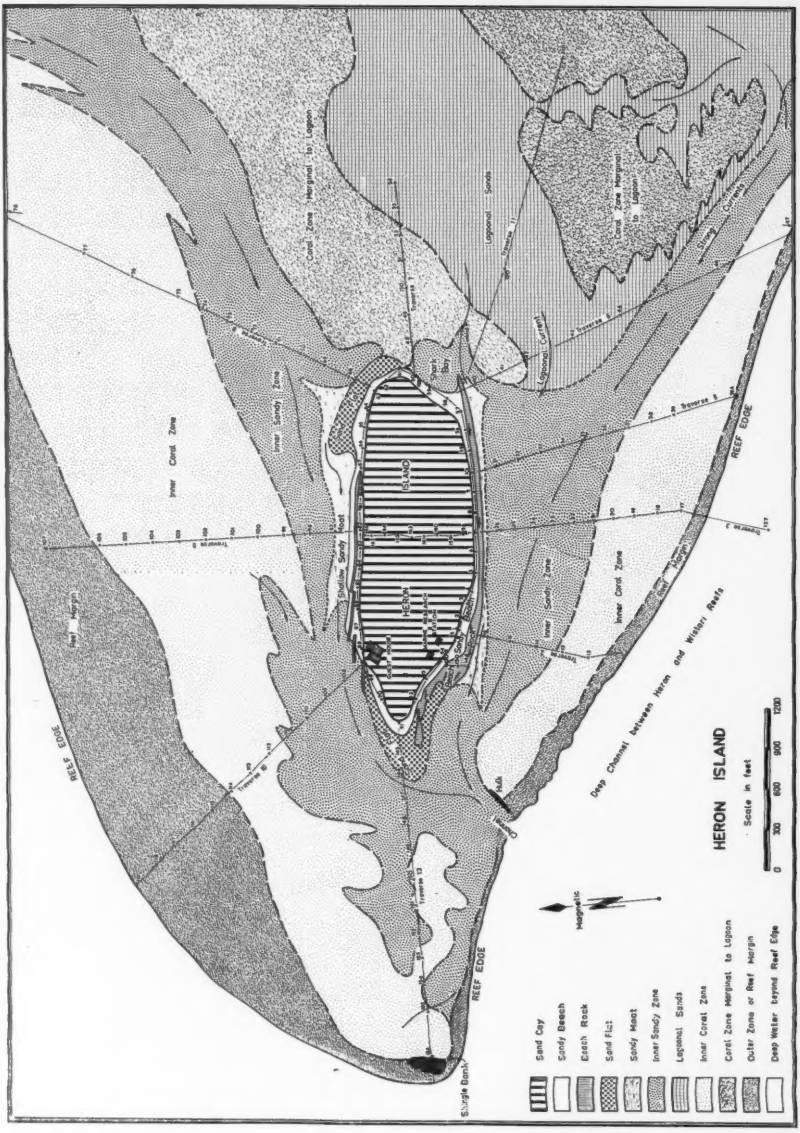

FIG. 2.—Physiographic-faunal zonation of the reef flat.

patches are restricted to narrow channels which average 8 ft in width and 4 ft in depth and are generally parallel with the reef edge. The zone varies from 50 to 150 ft on the southern side and is as wide as 900 ft in the north. Much of it is above sea level at low tide. On the western extremity of the flat, the coral shingle has been heaped into a comparatively high bank, 300 ft long and 2 to 3 ft above low tide level.

Reef Edge.—The reef edge may be considered to include part of the outer zone of the reef flat, or it may be restricted to the narrow seaward sloping band bordering the higher outer zone. Again, algal encrustation is a dominant feature and has resulted in the formation of a strong wave resistant front to the reef. Little detrital material is retained in the reef edge, although small isolated pockets of sand do occur.

Lagoon.—The lagoon occupies the eastern part of the reef platform and is the major physiographic feature. It is bordered by a wide, though discontinuous zone of living coral (fig. 7h), but the greater part of the lagoon consists of wide stretches of sand with coral patches of varying density. The western end varies in depth from 15 to 20 ft. Depths near the centre and eastern end are not known. The lagoon was not studied in detail under the present project.

Faunal Distribution

The broad faunal units correspond rather closely with the physiographic subdivisions.

Beach Rock.—Communities of the gastropod *Melaraphe* inhabit the higher parts of the beach rock, while *Nerita albicilla*, *Planaxis sulcata* are the dominant species on the lower, seaward slope. The chiton (*Acanthozostera*) is also abundant on the lower slopes. Areas where the chitons have been attached are more susceptible to erosion and develop into rounded or ovate depressions. All but the highest margin of the beach rock is covered by algal slime. The entire zone is exposed at low tide and submerged at high tide.

Inner Sandy Flat.—The inner sandy flat and beach rock are separated by the moat which is comparatively barren of fauna. The sandy flat is marked by occasional clumps of coral, now mainly dead, sand-filled, and overgrown with brown algae. Diagnostic species include *Acropora hebes* and *A. cuneata* and small massive corals such as *Goniastrea benhami*. The tops of the coral clumps are exposed at low tide. On the northern reef flat colonies of gastropods—*Conomurex luhanus* and *Strombus gibberulus*—are common. Black beche-de-mer (*Holothuria*) and the clam *Tridacna* occur throughout this zone and beyond to the outer coral-algal zone. The living coral clumps become more numerous seawards, and the inner sandy flat fauna grades into that of the inner coral zone.

Inner Coral Zone.—Branching corals such as *Acropora hebes*, *A. pulchra*, and *A. aspera* cover much of this zone. Massive corals—*Favites abdita*, *Goniastrea*, and *Goniopora* are also abundant. Less common are the micro atolls of purple *Porites* and brown *Platygyra*. *Seriatopora hystrix*, *Pocillopora damicornis*, the red "organ-pipe" coral *Tubipora musica*, and *Fungia* are diagnostic if not abundant. The exposed tips of the coral become increasingly encrusted seaward with the calcareous algae *Lithothamnion*, and the fauna passes into that of the next zone.

Reef Flat Margin or Outer Coral-Algal Zone.—*Lithothamnion* almost completely encrusts and fills the spaces between coral branches, producing a solid pavement. Sheets of coral debris composed mainly of *Acropora*, as well as nigger heads and broken coral rock, occur along this margin. Gaps and crevices in the pavement afford protection for the gastropods. *Turbo speciosus*, *Trochus niloticus*, and *Haliotis*. This is also the habitat of numerous echinoids, the most common being *Echinometra mathaei*, while *Heterocentrotus mamillatus* and *Diadema setosa* occur in lesser abundance. Boring lamellibranchs such as *Tridacna crocea* and *Lithophaga* also occur. Colonies of the soft coral *Polythoa caesia* are fairly common on the pavement surface. The nigger heads support barnacles (*Tetraclita vitiata*) and the oyster *Crassostrea amasa*.

Reef Edge.—Spreading, tabular, and dish-like species of *Acropora* as well as the branching forms already recorded inshore, flourish along the reef edge. Typical species include *Acropora hyacinthus*, *A. palifera*, *A. digitifera*, *A. cymbicyathus*, *A. corymbosa*, *A. acuminata*, and *A. intermedia*.

FIG. 2.—Physiographic-faunal zonation of the reef flat.

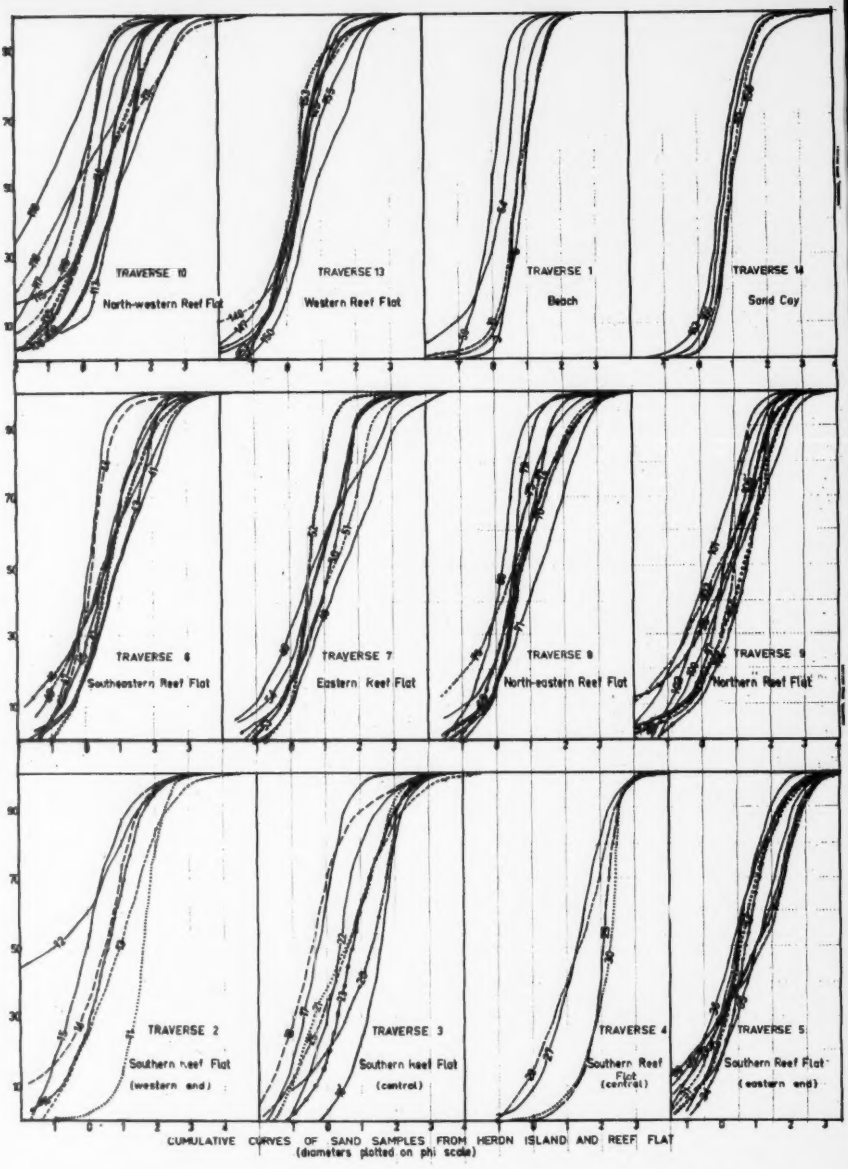

FIG. 3.—Cumulative curves of reef flat and cay sands grouped according to traverses.

REEF SEDIMENTS

General Observations

The reef sediments consist almost entirely of carbonates derived through the physical destruction of reef organisms. Such detritus is the major component of the reef platform, being far in excess of living organisms even in the zones of most vigorous organic growth. Coral and algal detritus form the bulk of the sediment, while subordinate fractions include foraminiferal, molluscan, bryozoan, and echinodermal debris (fig. 8a–f). The complete absence of oolitic or other accretionary material and the lack of dolomitization in the Heron Island reef sediments is in accord with observations made on other parts of the Great Barrier Reef. In these respects the Queensland reef province is quite distinct from those of the Bahamas and Pacific Atolls and from many of the ancient reef provinces. The significance of these features is not well understood, but it is obvious that they have important bearing on the interpretation of sedimentary processes operative in the various provinces. It is believed, in the light of recent work, that the absence of such material reflects a low degree of direct carbonate precipitation from sea water. Furthermore, the extremely small proportion of material finer than .065 mm (that is, silt and clay sizes) in all the samples analysed supports the theory that chemical precipitation is not widespread on the reef flat. The organic framework of coral and algae provides a continuous rim around the reef flat and thus prevents much of the detritus from being swept into the surrounding sea. In addition, the regions of denser organic growth (inner-coral and outer-coral algal zones) provide effective sediment traps. Sand carried into these areas is protected from severe wave and current action and suffers little re-working. The inner sand flat, where coral and algal growth is more restricted, is subject to more intensive wave and current action and provides a less permanent depositional environment. Considerable quantities of sand are swept off the flat through channels in the reef margin. Sands trapped in the reef framework differ markedly in their textural character from those found on the more exposed sandy flat (see fig. 3 for cumulative curves of sands from the different environments).

Wave, current, and wind are responsible for transportation and reworking, and consequently movement and deposition of sediments may vary considerably with seasonal changes. At the present time deposition appears to be occurring along the northeastern (fig. 7g) and western margins of the island, while banks of coral shingle are forming on the western extremity of the reef flat. The southwestern channel which crosses the reef edge near the hulk undoubtedly carries large quantities of reef flat detritus into the deeper sea, but there is no evidence to suggest that the sand cay—Heron Island—is being eroded. On the contrary, it would seem that the island is expanding. Comparison of Steer's (1938, p. 61) survey with the present map of the island shows that the northeastern shoaling has been in progress for at least the past 22 years while deposition on the western end may have begun more recently.

The sands of the island above high-tide level are quite distinct from those of the beaches and reef flat, and reflect different conditions of sedimentation.

Because of the vigorous activity of the abundant beche-de-mer and other organisms of similar feeding habit, only a small proportion of sediment escapes passage through intestinal tracts. The equally vigorous burrowing and excavating of the land fauna results in similar reworking of the island's sands.

Textural Variations

Used in conjunction with composition analyses, textural measurements, such as the sorting coefficients and average size values, permit the recognition of several sand facies within the reef flat. These measurements, as shown on the accompanying maps, also reflect the strong control exerted by physiography, faunas, and currents over the distribution of the different sand types. The textural study was based on more than 150 bulk samples and an equal number of orientated samples collected at intervals of 200 and 300 ft along radial traverses from the island to the reef edge. The orientated samples collected in flat tins were impregnated with Polylite plastic resin, sectioned, polished, and the dominant grain direction

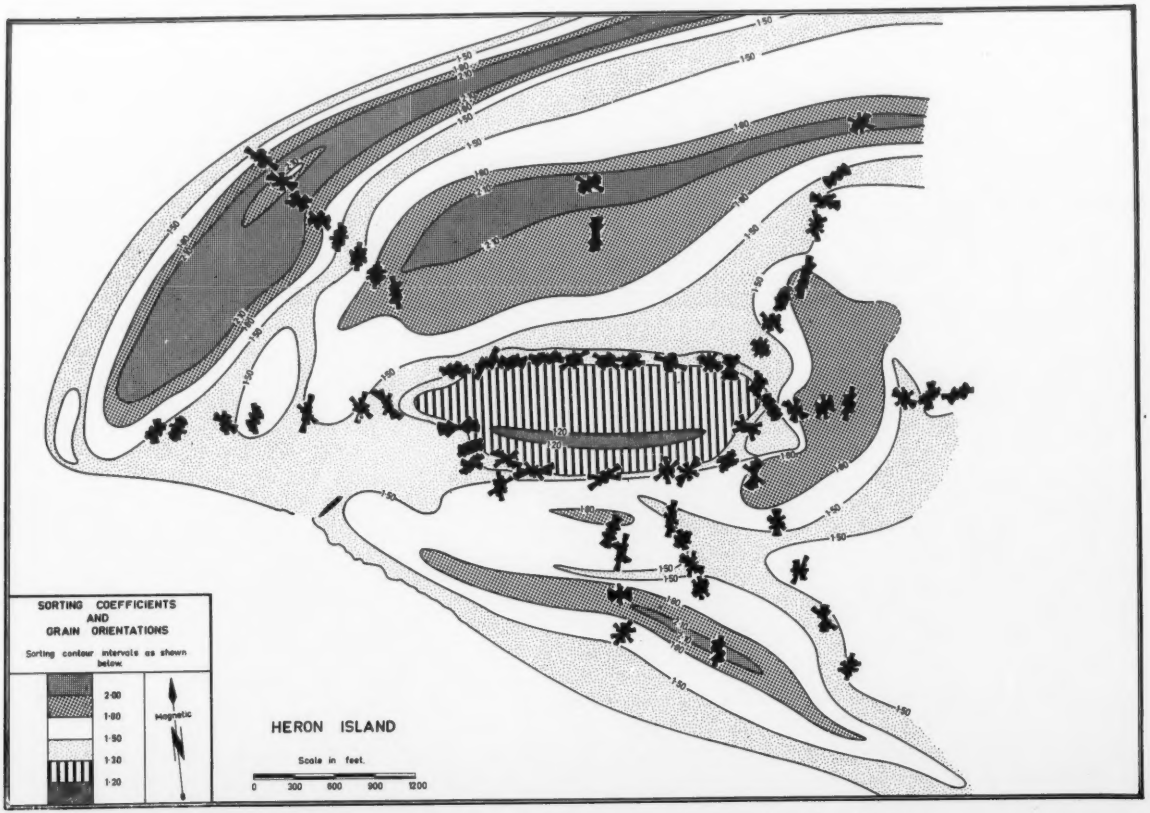

FIG. 4.—Isopleth map showing variation in sorting and grain orientation of sands.

determined. The bulk samples were dried, mechanically analysed and examined under a binocular microscope. Thin sections cut from the orientated samples were examined under a petrological microscope.

Results of mechanical analysis have been plotted on two maps where sorting coefficients, medians and modes reflect the physical distribution patterns. In general these patterns show a close correspondence with the physiographic pattern of the reef. In Figure 4, where sand distribution has been plotted in terms of the sorting coefficients, it is seen that the best sorted material is restricted to the beaches, the inner sandy flat, and the reef edge. The expanding shoals on the northeastern and western margins of the island are well sorted, while sorting in the inner and outer coral zones and in the coral zones bordering the lagoon is very poor.

The relationship between sorting and the physiographic pattern is not an unexpected one. The beaches and reefedge are subject to intensive wave action, while the inner sandy flats are on the paths of the main currents flowing westward from the lagoon and reef flat. The coral zones, on the other hand, are in the region of least wave action, and the dense organic growth shelters the small sand patches from such action. The sands of the cay show the highest degree of sorting and a uniformity of character across the island. Other textural features subsequently discussed suggest that the surface sands at least were transported by wind. Observation of dry sand movement from the southern beach during heavy wind storms confirms this suggestion.

Analysis of the median and modal values of the samples produces a distribution pattern as shown in figure 5, which is similar to that of the sorting coefficients. Sediments with the coarsest medians occur along the outer half of the northern reef margin and the reef edge. The high values reflect the preponderance of coral shingle which represents a passing phase in the sedimentary process, the shingle being in a state of incomplete breakdown. Constant wave action along the reef edge reduces much of the shingle to finer grades which may be carried inshore over the reef flat or swept seawards and lost to the deeper environments beyond the reef. These coarse sediments have a high degree of sorting because of the rapid removal of fine detritus.

The second highest median values also occur in the outer half of the northern and southern reef margins. As with the outer shingle belt, this material is still in the process of breakdown. However, since it is further from the reef edge and is subject to less intensive wave action, it is poorly sorted. Sands and shingle with similar medians occur on the western half of the inner sand flat in the south where the extremely narrow distance between reef edge and sand cay has resulted in the spreading of this "unreduced" material across several physiographic zones. However, the southern currents across the sandy flat have produced good sorting, thus enabling distinction of these sediments from those of the reef margin.

The third grade of median values is found in the inner coral zone. Sands with similar medians occur in the inner sandy flat in the southwest, along the northern moat, and in lagoonal channels. Again, these are distinguished by their better sorting.

Finer medians occur along the inner parts of the reef margin and in the coral zone as well as on the inner sandy flat and over a wide area of the lagoon. Differences in sorting distinguish the three environments. Sands with the finest medians occur within the inner coral zone.

Distribution of Sediments

In general, the degree of physical breakdown of sands is such that determination of the parent organisms is difficult. However, attempts have been made to analyse the sediments in terms of their main faunal constituents: corals, algae, molluscs, crustacea, foraminifera, bryozoa, and the easily recognized red coral, *Tubipora*. Differences in texture as well as composition permit the identification of sands deposited in the four main environments—island, reef flat, lagoon, and channel—although many features are common to all four. The reef flat sands may be separated into the northern and southern facies and these are divisible into still smaller types as shown on figure 6.

The sands above the high tide mark on the island show high degrees of sorting, round-

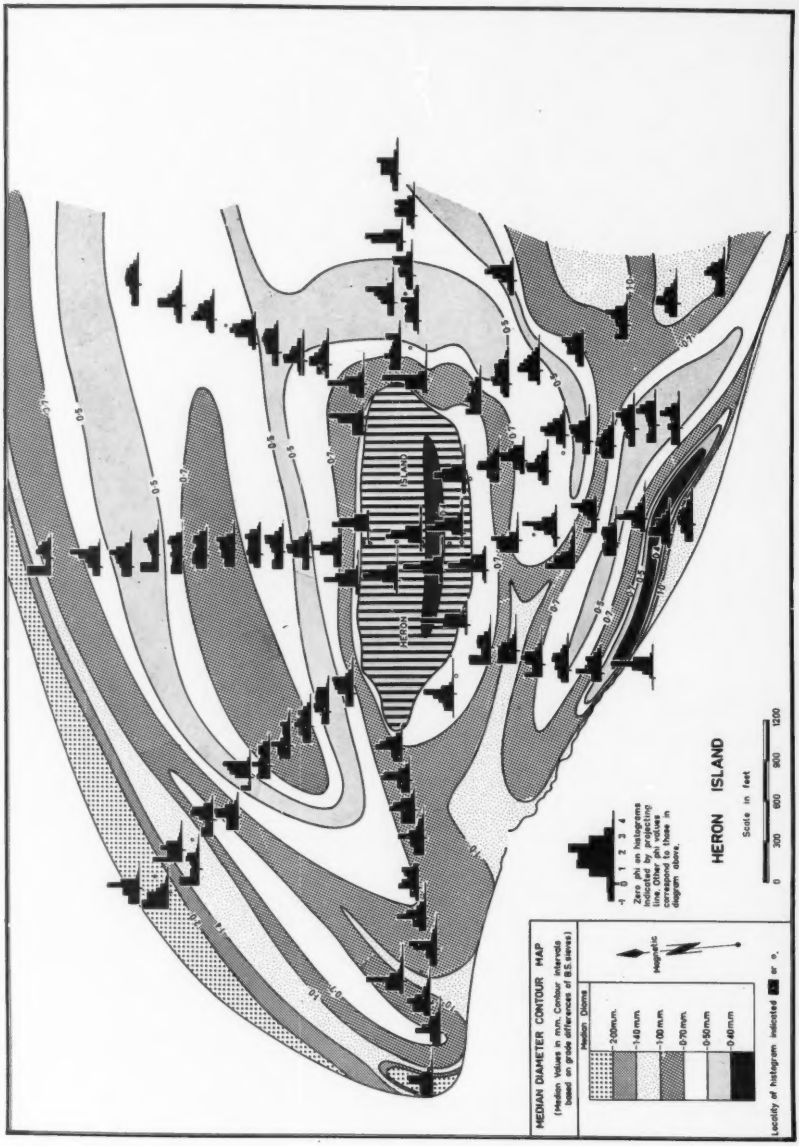
MEDIAN DIAMETER CONTOUR MAP
(Median Values in mm. Contour intervals based on grade differences of B.S. sieves)
Median Diams
-200m.m.
-140 m.m.
-100 m.m.
-070 m.m.
-050 m.m.
-040 m.m.
Locality of histogram indicated by arrow.
Magnetic
Zero phi on histograms indicated by projecting lines on the profiles correspond to lines in diagram above.
-1 0 1 2 3 4
HERON ISLAND
Scale in feet
0 300 600 800 1200

FIG. 5.—Distribution of median diameters.

ing, and sphericity; they are extremely fine grained and many of the grain surfaces are pitted. All these features are suggestive of wind action. Faunal components appear to be similar to those of the reef flat sands, except for the noticeable lack of *Tubipora* and bryozoan detritus. Badly worn tests of *Calcarina* occur on the northern side of the island, but not on the higher southern part. Decaying vegetation has stained the sands so that they now have a dirty brown colour. The possibility of solution of the carbonate by weak humic acids may account in part for the finer grain size of these sands.

The reef flat sediments exhibit a variety of texture and composition, but grains are mostly angular to subrounded with a tendency towards increasing sphericity in the finer grades. Grain surfaces are smooth. The major division of the flat, based on sedimentary character alone, is into northern or leeward and southern or windward provinces. In both provinces the sediments are predominantly coralline and algal in origin. This is more apparent on the southern flat where faunal variety is somewhat restricted. On the northern flat, however, molluscan, crustacean, foraminiferal, bryozoan, and echinodermal fractions are conspicuous. It has also been found that where there is a more varied representation of faunal elements the tendency is towards good sorting, while restricted composition is frequently associated with poor sorting.

Because of the overwhelming dominance of algal and coralline detritus in the sands of the southern flat, variations in composition are difficult to recognize. Bryozoa and foraminifera are poorly represented while crustacean debris is almost completely lacking. Molluscan fragments on the other hand are abundant and reach their maximum concentration in the inner coral zone of the southern flat. *Tubipora* is restricted to the inner sandy zone where it is comparatively abundant.

On the northern reef flat there is a progressive increase in the bryozoan fraction away from the shore, to a maximum concentration in the outer coral-algal zone. *Tubipora* detritus shows a progressive increase shoreward. This material occurs in greater abundance on the northern flat. The living organism grows in the protected parts of the coral zones both on the reef flat and in the lagoon, and its detritus is swept shorewards by tidal and lagoonal currents. Foraminiferal debris is more prolific both in individuals and species on the northern flat. In the sands this material constitutes the bulk of the 0.5–1.0 mm grade, the most common species being *Calcarina hispida* and *Baculogypsina sphaerulata*. *B. sphaerulata* becomes more abundant towards the reef edge. *Marginopora vertebralis* is the main species of larger foram, and its distribution pattern is similar to that of the bryozoan detritus, that is increasing seawards. It rarely occurs in great concentrations.

Glauconite and terrigenous minerals which were recorded in the Heron Island Bore (Richards and Hill, 1942) were not detected in any of the reef flat samples.

The few lagoonal samples showed faunal elements similar to those of the reef flat but in different proportions. Bryozoan and molluscan detritus constitute the bulk of the coarser fractions, coralline and algal material is also abundant, and forams are sparsely distributed. The rare specimens of *Calcarina* are badly worn, suggesting considerable movement through wave action at their source, which is probably the reef margin. Texturally, the grains are well rounded and of low sphericity, thus suggesting prolonged but gentle attrition in contrast with the more severe abrasion typical of the reef flat.

The channel to the south of the reef platform was sampled in five places from depths ranging from 60 to 100 ft. The sands are typically unrounded and of low sphericity. The most abraded material is that which has been washed down from the reef flat. However, this does not constitute the major fraction. Skeletal fragments of the foraminiferal species *Alveolinella quoyi*, *Operculina bartschi*, and *Heterostegina* make up the bulk of the sand together with much worn echinodermal detritus, *Marginopora vertebralis*, *Tubipora*, and *Acropora* derived from the reef edge and reef flat.

The sand facies map (fig. 6) reflects the close relationship between sand type, faunal distribution, current pattern, and physiographic zones. Faunal variation has been largely responsible for the primary separa-

FIG. 5.—Distribution of median diameters.

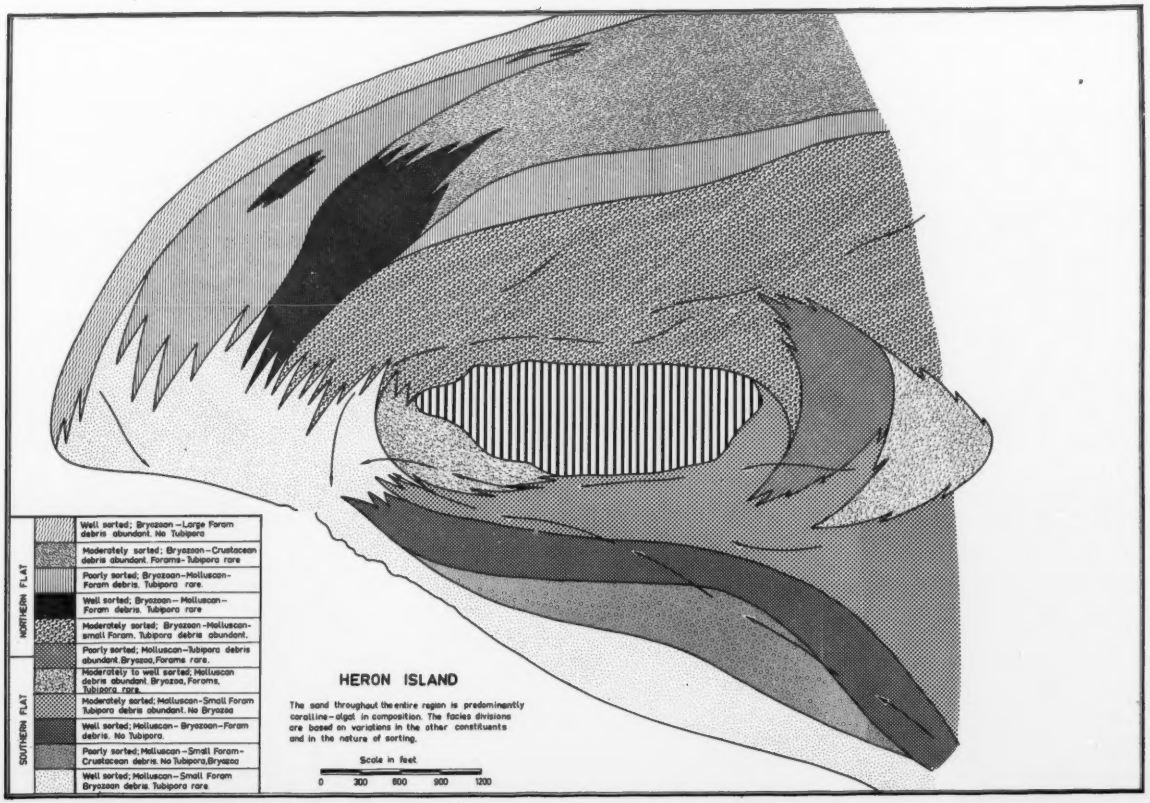
NORTHERN FLAT
SOUTHERN FLAT
Well sorted; Bryozoan – Large Foram debris abundant. No Tubipora
Moderately sorted; Bryozoan – Crustacean debris abundant. Forams- Tubipora rare
Poorly sorted; Bryozoan–Molluscan-Foram debris. Tubipora rare.
Well sorted; Bryozoan – Molluscan–Foram debris. Tubipora rare
Moderately sorted; Bryozoan–Molluscan-small Foram. Tubipora debris abundant.
Poorly sorted; Molluscan–Tubipora debris abundant. Bryozoa, Forams rare.
Moderately to well sorted; Molluscan debris abundant Bryozoa, Forams, Tubipora rare.
Moderately sorted; Molluscan–Small Foram Tubipora debris abundant. No Bryozoa
Well sorted; Molluscan – Bryozoan–Foram debris. No Tubipora.
Poorly sorted; Molluscan – Small Foram–Crustacean debris. No Tubipora, Bryozoa
Well sorted; Molluscan–Small Foram Bryozoan debris. Tubipora rare.
HERON ISLAND
The sand throughout the entire region is predominantly coralline–algal in composition. The facies divisions are based on variations in the other constituents and in the nature of sorting.
Scale in feet
0 300 600 900 1200

FIG. 6.—Sand facies map of Heron Island reef flat.

tion into northern and southern sand facies. The northern flat offers a more favourable environment to Foraminifera, Bryozoa, and *Tubipora*, all of which make significant contributions to the northern sands, whereas the more exposed southern flat supports only small populations of these groups. The faunal distribution is strongly influenced by the physiographic pattern, and a similar influence is exerted on the sand distribution.

The conspicuous *Tubipora* sands occur in the path of the main current from the northern part of the lagoon while the smaller expanse on the southern flat is swept by the southern lagoonal current. It seems that the main source of *Tubipora* detritus is in the coral zones marginal to the lagoon. Tidal action tends to concentrate it inshore, once the lagoonal currents have brought it on to the inner sandy zone of the reef flat. The disappearance of *Tubipora* from the sands towards the western end of the flat probably results from the cumulative effects of wave action on the fragile coral debris during its passage across the shallow reef flat to the southwestern channel. At its source in the deeper water of the lagoon, the detritus suffers only a small degree of physical breakdown. The lagoonal current carries this largely unabraded material into the shallow inner sandy zone where wave action is more severe. By the time that it has reached the western end of the reef its destruction is complete and only the very fine grades, which are impossible to identify, remain. On the more exposed southern flat, where wave action is most severe, destruction of the *Tubipora* debris is probably more rapid, thus accounting in part for its more restricted occurrence.

Foraminifera and Bryozoa appear to thrive mainly on the northern and northwestern reef margin. They are broken down by wave action along the reef edge and swept shorewards by tidal movement. The maximum concentration of their debris is near the site of the living organisms. Shoreward, there is a marked decrease in bryozoan detritus possibly because of its greater susceptibility to abrasion and the action of the currents across the flat. Foraminiferal material also decrease shorewards, but to a lesser extent than the bryozoan detritus, possibly because the factors influencing the latter are less effective on the more resistant foram tests.

FIG. 6.—Sand facies map of Heron Island reef flat.

Grain Orientation

The analysis of grain directions has revealed a somewhat complex orientation pattern. In the majority of samples there is a strong secondary direction, while in some there is even a third direction. The complexities appear to be the result of interference between reef flat currents and normal tidal movements across the flat. When considered in relation to the known water movements, the grain orientation pattern becomes less obscure. The results of this study emphasize the difficulties involved in the interpretation of current and source directions in ancient environments when the basis of such interpretation is grain orientation. Without adequate knowledge of the current, wave, and tidal movements in the Heron Island region, the grain orientation patterns would be without meaning. Furthermore, if the density of sampling were not sufficiently high, it would be possible to obtain orientation patterns which were contrary to the known current directions. It is obvious then that deductions drawn from similar measurements in ancient sediments may be quite unreliable, especially when the density of sampling is low, which is frequently the case. Grain orientation can be used safely only when considered in relation to other directional properties and to the overall distribution of the sands.

From the reef edge to the inner margin of the coral zone, the main influence is tidal and the dominant grain direction is more or less radial to the island. However, a narrow zone near the reef flat margin is swept by a southwesterly flowing current on the northern flat and the normal radial orientation tends to be obscured by a south-west component. Along the inner sandy flat where the main currents flow towards the west, grain orientation clearly reflects the current direction. On the eastern end of the island interference between current and wave action has resulted in two and occasionally three components of similar magnitude in the beach sands. However, the normal parallelism of sand grains with the shore line is very evident on the other beaches.

In general, grain orientation in the sands

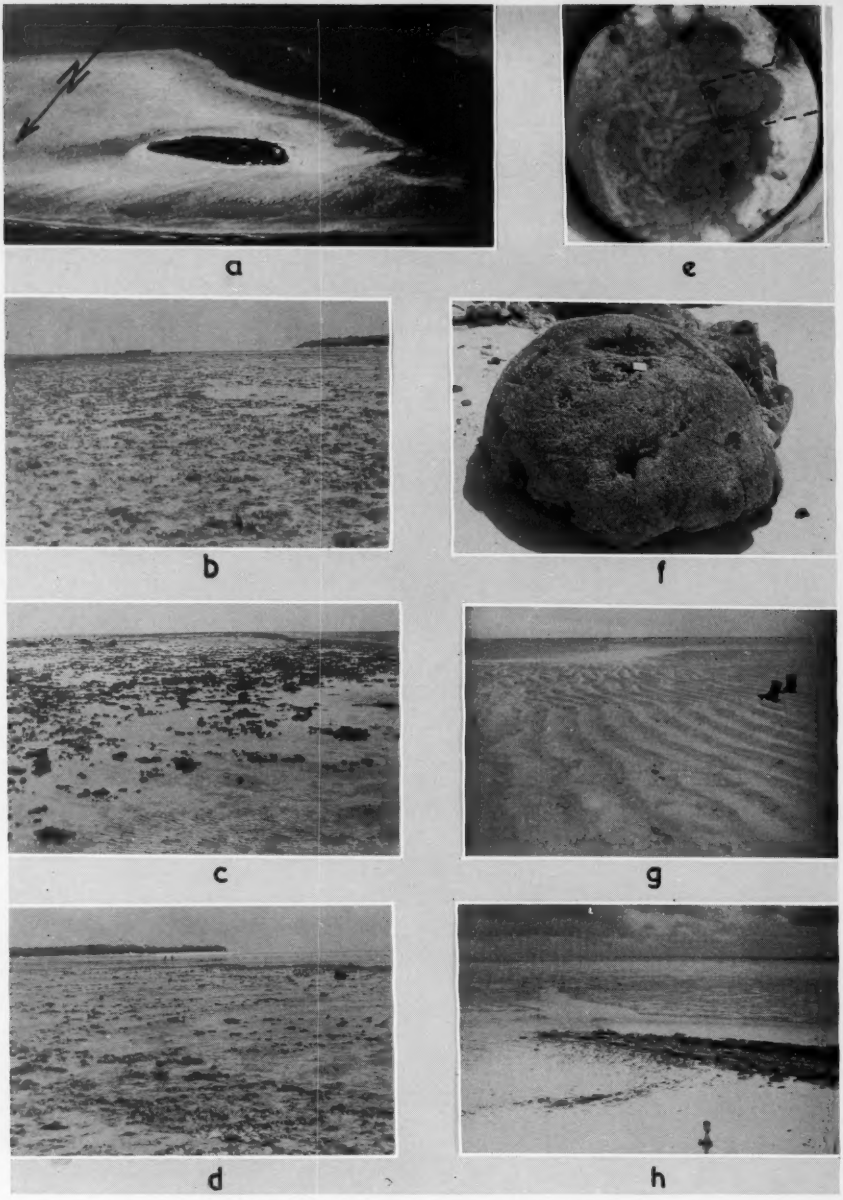

FIG. 7.—Heron Island Reef. a. Aerial view of western end, looking southeast. b. Southern reef flat looking west. c. Southern reef margin, looking east. d. Northern reef flat looking south from reef edge. e. Beche-de-mer and mounds of faecal pellets. f. Coral nigger head. g. Ripple marked sand shoal on northeast end of sand key. h. Beach rock spit on southeast tip of island with lagoon in far distance and channel through marginal coral zone into southern moat.

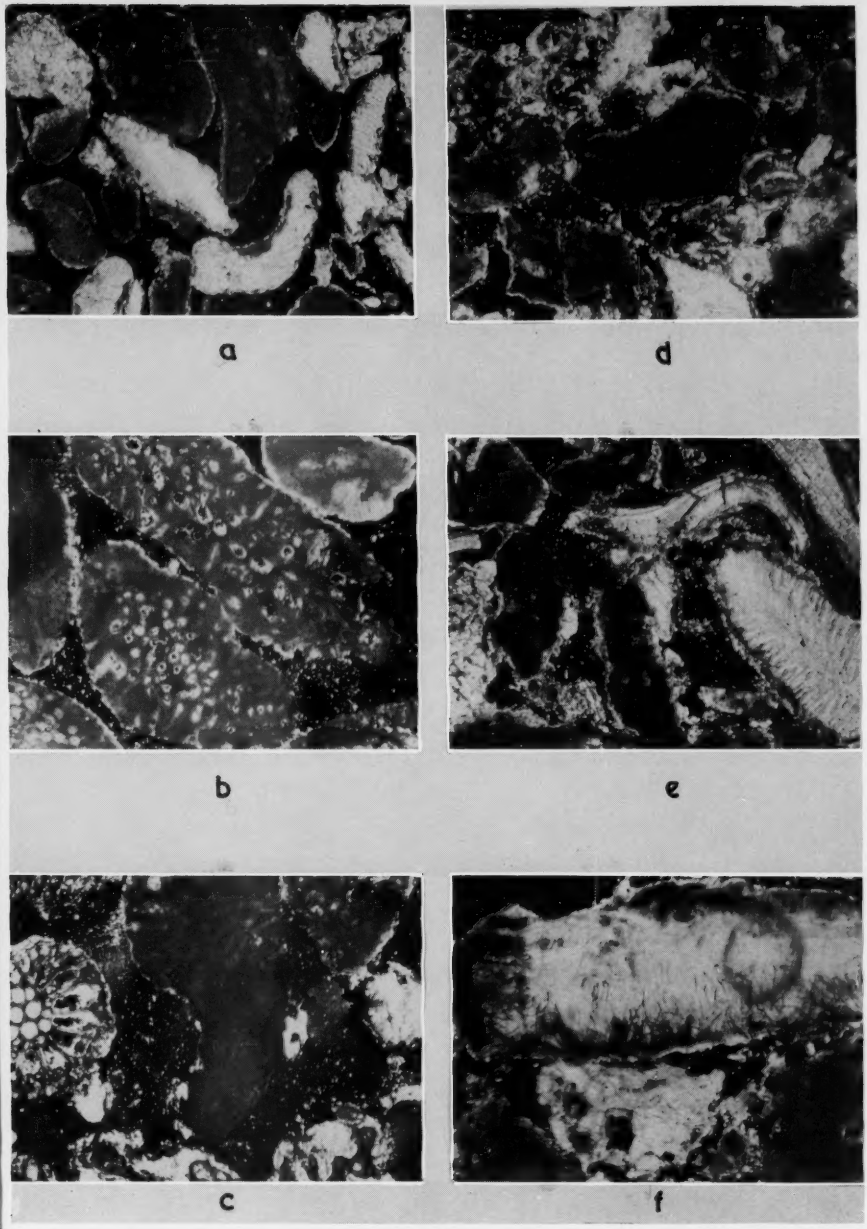

FIG. 8.—Photomicrographs of reef sands. a. *Halimeda-Acropora* sand, locality 1, south beach ×27. Most grains with fine carbonate fringe. b. *Halimeda* sand locality 60, north beach ×27. c. *Foram-Halimeda-Acropora* sand locality 60, north beach ×27. d. *Foram-Halimeda-Lithothamnion-Coral* sand, locality 31 S.E. reef flat ×27. e. *Molluscan-Algal-Coral* sand, locality 31, ×27. f. *Acropora-Halimeda* sand; coral fragments with algal borings; from locality 31, ×45.

of the southern flat is more strongly influenced by tidal movement, and the effect of currents is less evident. This is because of the narrow width of the southern flat, and the stronger influence of prevailing southeast winds.

CONCLUSION

The results of the present study have shown that skeletal detritus is the most abundant component of the sand cay and reef flat, being far in excess of living organisms. Furthermore, the main constituent of both sediment and organism is calcium carbonate, which averages more than 95 percent of the total composition. Magnesium carbonate and organic material make up the remaining 5 percent. The main sources of sediment are the corals and algae which grow in greatest profusion in the reef margin and the seaward part of the inner coral zone. Widespread and continuous destruction of the living organisms by severe wave action around the margin on the reef provides an endless supply of material which is carried shoreward by tidal action or swept towards the southwest by currents. In its passage across the shallow reef flat, and particularly on the inner sandy zone where the sparseness of living coral clumps affords little protection, the skeletal detritus is subjected to continuous wave action and gradually reduced to finer grades.

Diagnostic features of the sands from different parts of the reef are provided by the less abundant constituents, which are also more restricted in their distribution. These constituents—detritus from Bryozoa, Foraminifera, and *Tubipora*—depend on the distribution of the living organisms, their resistance or lack of resistance to abrasion, and the pattern of currents.

Granulometric studies have shown a pattern of textural variation in the sediments which corresponds closely with the physiographic, faunal, and current patterns. Combined with the diagnostic constituents, textural characters such as sorting, median, and modal values, and rounding, make it possible to distinguish different sand facies on the reef flat.

Grain orientation measurements again reflect the relationship between sediment and current-wave pattern. Strongest directional measurements were obtained from the beaches where the breaking waves are the only factor involved. The effect of currents on grain orientation is evident where the lagoonal currents sweep across the flat. However, where both currents and wave action are of equal importance—in the inner coral zones and reef margin—directional properties are poor.

The sands of the cay are readily distinguished from those on the flat. They are extremely well sorted, fine-grained and rounded. The difference between them and the reef flat sands is believed to be caused by wind action, and to a lesser degree by solution by rain water.

ACKNOWLEDGMENTS

The authors are indebted to the Great Barrier Reef Committee for providing the facilities of the Marine Research Station at Heron Island, to Professor R. H. Greenwood of the Geography Department, University of Queensland for permitting the use of his map of the southern reef flat and island, to Mr. D. J. Belford of the Bureau of Mineral Resources, Canberra, for determination of foraminiferal samples, and to Mr. A. G. Smith of the University of Queensland for technical assistance. All laboratory work was carried out at the Heron Island Marine Station and the Department of Geology, University of Queensland.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 31, NO. 2, PP. 231–244
PLATES 1–2, FIGS. 1–4, JUNE, 1961

LATE PENNSYLVANIAN AND EARLY PERMIAN LIMESTONE PETROLOGY AND CARBON ISOTOPE DISTRIBUTION, GLASS MOUNTAINS, TEXAS[1]

CHARLES A. ROSS AND SHINYA OANA
Illinois Geological Survey, Urbana, Illinois and Faculty of Science, Nagoya University

ABSTRACT

The environment of deposition and diagenetic changes of some of the Late Pennsylvanian and Early Permian limestones of the Glass Mountains, Texas, are closely reflected in their field relations and in their texture and particle composition as determined by thin section investigations.

From analysis of stable carbon isotopes the fine grained, light colored, algal limestones indicative of an oxidizing environment have distinctly positive δC^{13} values, whereas fine grained, dark colored, fetid limestones indicative of reducing environments have markedly negative δC^{13} values. The coarse grained limestones having abundant sparry calcite cement have δC^{13} values near zero, that is, a C^{13}/C^{12} ratio near the standard, Chicago PDB, a belemnite. These C^{13} values suggest that the source of the sparry calcite cement is at least in part from CO_2 produced by methane fermentation of organic material in the substrata.

INTRODUCTION

The Glass Mountains disclose late Pennsylvanian and Permian strata which were deposited on the northern flanks of the Marathon orogenic belt. These beds thicken and thin abruptly along their strike and have sharp changes in facies and numerous unconformities. The excellent exposures, abundant fossil faunas, and lack of structural complications make this sequence ideal for studying depositional environments.

In studying the fusulinids from this succession (Ross, 1959a), the wide range of limestone types became strikingly apparent and Oana kindly undertook to determine the carbon 13/carbon 12 isotopic compositions of the various types of limestone as an aid to analyzing the conditions of deposition and post-depositional changes which have taken place in these limestones. Our primary object was to attempt correlation between various limestone types and their carbon isotope composition, but the large number of variables in such a study permit us to make only tentative suggestions as to such a relationship. Our foremost difficulty was the lack of information available on carbon isotope distribution in various rock types and marine organisms. In interpreting our data, it seems that the original carbon isotopic composition of the calcareous particles of the rock is of first importance in the distribution of carbon isotopes in many limestones. However, if during diagenesis the carbon isotope composition is variously modified by removal and/or replacement of calcite, what evidence is preserved in the rock and how does petrographic analysis together with carbon isotope data aid in determining these changes?

The 200 limestones which have been studied from the late Pennsylvanian and early Permian represent almost a complete sampling of the succession. Approximately 100 samples were studied in thin sections, and 32 of these were analyzed for their carbon isotopic composition.

STRATIGRAPHY AND PETROLOGY OF THE LATE PENNSYLVANIAN AND EARLY PERMIAN STRATA

Three rock successions, each distinctly important in its own right, have been examined in detail. These are the type section of the Gaptank Formation of late Pennsylvanian age; the type section of the Neal Ranch Formation of the lower part of the Wolfcamp Series, Permian; and the type section of the Lenox Hills Formation of the upper part of the Wolfcamp Series and the lower part of the overlying Leonard Series, Permian (figs. 1 and 2). By tracing beds laterally and by studying the fusulinid faunal zones, the vertical sequence of these

[1] Manuscript received May 9, 1960.

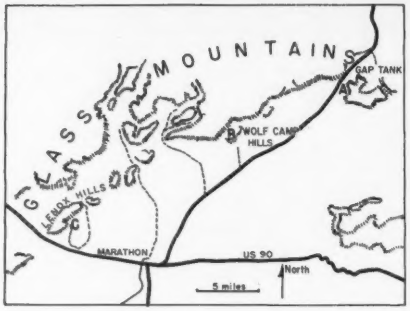

FIG. 1.—Index map of localities; A, type locality of the Gaptank Formation; B, type locality of the Neal Ranch Formation; C, type locality of the Lenox Hills Formation, and lower part of the Leonard Series.

sections was established by Ross (1959a and 1959b).

The depositional patterns of the Gaptank, Neal Ranch, Lenox Hills, and lower part of the Leonard formations were determined and closely controlled by the highly active Marathon orogenic belt immediately to the south of the Glass Mountains escarpment and the rapidly subsiding Val Verde geosyncline to the north. The late Pennsylvanian and early Permian near-shore deposits of the Glass Mountains change facies northward into this geosyncline and pass into black shaly sandstones and thin limestones across a short distance.

In the belt of outcrop along the escarpment, these near-shore deposits are a complex of intertonguing shallow water sediments which contrast strongly with the older, deeper water sediments exposed in the Marathon basin. Unconformities and lenses of coarse conglomerate of both regional and local extent dominate much of the stratigraphic succession, and it appears probable that during this time not only major movements but many minor ones related to the Marathon orogenic belt disrupted the sedimentation patterns.

The folding, the unconformities, and the associated thick lenses of conglomerate within the lower part of the Gaptank Formation (late Desmoinesian or early Missourian) and at the base of the Lenox Hills Formation (middle Wolfcampian) attest to the time and place of two major orogenic movements of regional intensity. It is probable that these major movements led to instabilities which caused various décollements (thrust and fold thrust faults, King, 1937) in the Marathon fold belt. One of these décollements consists of displaced middle Pennsylvanian and older strata, and a later one consists of displaced beds as young as Neal Ranch age (Ross, 1959a and 1959b).

Gaptank Formation

The oldest limestones studied come from the type area of the late Pennsylvanian Gaptank Formation at Gap Tank, 28 miles northeast of Marathon, Texas (fig. 2A). Here the Gaptank Formation is composed of three contrasting rock types; a lower 50 ft thick siltstone and limestone unit, bearing *Chaetetes*, which is unconformably overlain by a 550 ft thick limestone conglomerate and shale sequence, grading upwards into an 870 ft thick shale and limestone succesion.

The upper shale and limestone beds of the Gaptank Formation are well exposed for about 10 miles to the west of Gap Tank and present a complex facies of intertonguing lithologies. Individual limestone beds thicken and thin and may pinch out across short distances. Locally the constituents of these limestones may be wholly calcitic or may include some quartose silt and clay. Many of the limestones show biohermal crossbedding which is particularly distinctive in rocks having a large percentage of crinoid columnals. Most of the limestones are light gray and, although locally massively bedded, are elsewhere commonly in 3 in to 2-ft beds. A few beds are mottled and have 2 or 3 shades of fine calcite matrix intermixed in irregular patches with vague gradational outlines between boundaries.

The facies relations in the Gaptank Formation indicate deposition of the beds in shallow water, near shore environments locally having large bioherms or banks of shell debris separated by areas of shale and sand deposits. The terrigenous sand, silt, and clay constituents were derived from the middle Pennsylvanian Marathon uplift to the south. These siltstones and sandstones weather orange-brown and suggest the presence of iron compounds originally in a re-

duced state, probably formed during or shortly after their deposition.

Following Folk's classification (1959), limestones from beds 43-9 and 43-10 (pl. 1, figs. 1 and 2) are biosparites and for the most part are fine grained calcirudites or coarse calcarenites. Gastropod and ostracod tests are recrystallized to a sparry calcite mozaic and patches of microsparry calcite are scattered throughout the matrix. Quartz and chert sand grains are common and make up 10 to 15 percent of these rocks.

Limestones from beds 43-11, 40-20, and 40-23 are biomicrites. A sample from 43-11 (pl. 1, fig. 4) contains scattered fusulinids, smaller Foraminifera, fenestrate bryozoans, and brachiopod and crinoid fragments and lacks algal plates or their relict outlines. Both 40-20 (pl. 1, fig. 5) and 40-23 contain abundant algal plates (inverted from aragonite to calcite) and other fossils are scattered throughout the matrix which is locally a microsparite. 40-20 has more than 30 percent algal remains and 40-23 has only 20 percent of these fragments.

Thin sections of samples from 43-15 (pl. 1, fig. 3) show this rock to be biomicrite having occasional outlines of recrystallized algal plates and (rarely) fusulinids or smaller Foraminifera.

The sample from bed 43-17 (pl. 1, fig. 6) at the top of the type section of the Gaptank Formation is one of the few fossiliferous bands in the bed. This fossiliferous rock is marginal between a biosparite and biomicrosparite and contains scattered fusulinids, smaller Foraminifera, stromatoporoids, and algal plates (inverted from aragonite to calcite).

Samples 22A-1 (pl. 2, fig. 1) and 22A-2 are from bed 2 of King's (1937) Wolfcamp section in the Wolf Camp Hills. Fusulinids from fossiliferous bands within bed 2 indicate a late Pennsylvanian rather than an early Permian age as assigned by King (1937). Both samples are biosparites containing brachiopods, bryozoans, algal and stromatoporoid fragments, and scattered fusulinids, smaller Foraminifera, and crinoid columnals. Worm burrowings and pellets are common (pl. 2, fig. 1). These samples show several different types of recrystallized materials in addition to the sparry calcite. Thus, some of the microcrystalline material

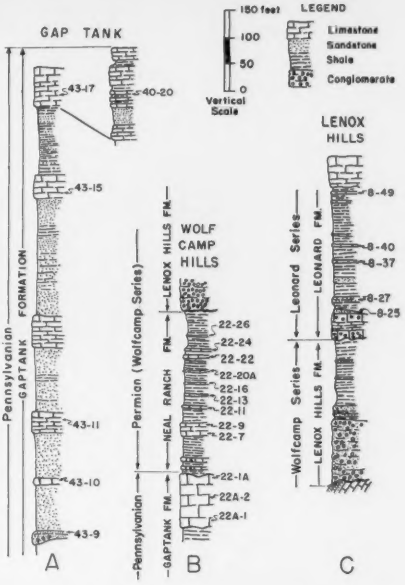

FIG. 2.—Stratigraphic sections; A. type section of the Gaptank Formation at Gap Tank; B. type section of the Neal Ranch Formation in the Wolf Camp Hills; C. type section of the Lenox Hills Formation, and lower part of the Leonard Series in the Lenox Hills.

is recrystallized to microsparry calcite, particularly in the pellets and worm burrows where grain boundaries are commonly brown colored, and isolated dolomite crystals occur within some of the algal masses.

Sample 22-1A (pl. 2, fig. 2) from the upper part of this limestone, King's bed 2, is a biosparite-biomicrite containing abundant relict algal outlines, bryozoans, and rare fusulinids.

This limestone, like many in the Gaptank Formation, is lenticular and the foreset conglomerate lenses near its base indicate that it was deposited as a reef. The biosparite and biomicrite lithology and the algal-stromatoporoid association indicate well sorted calcarenite lenses and poorly sorted accumulations of shell debris and calcareous muds in a shallow water environment.

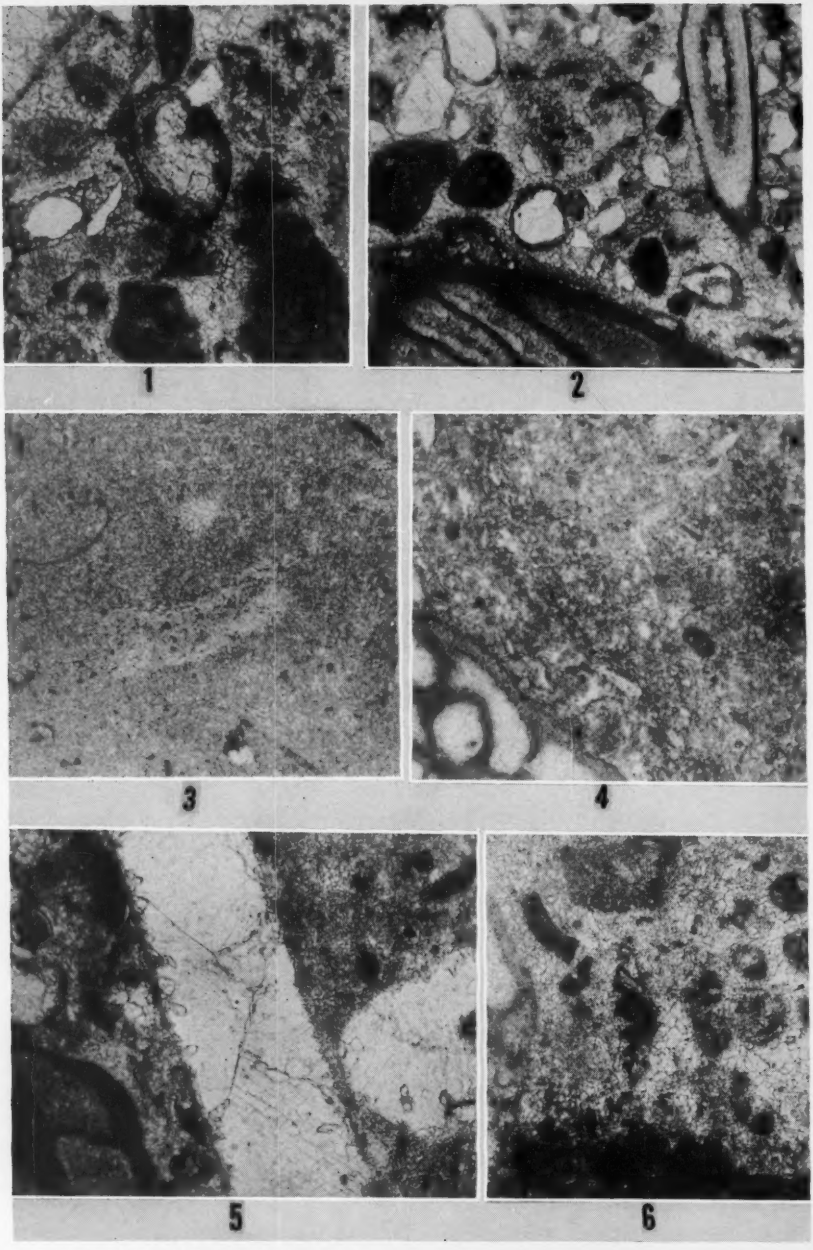

PLATE 1.—Photomicrographs ×50. Samples from the Gaptank Formation, near Gap Tank.

Neal Ranch Formation

The second sequence of limestones which was investigated is from the Neal Ranch Formation of the Wolfcamp Series (Permian). This formation is 350 to 450 feet thick in the Wolf Camp Hills, 14 miles northeast of Marathon (fig. 2B). It consists primarily of shale and thin, coarse calcarenite beds which alternate vertically, forming 17 or more repetitions of beds (cyclothems). Both the shales and calcarenites of this formation oxidize by weathering to orange-brown or light brown colors and are fetid on fresh surfaces.

The first few feet of shale overlying a calcarenite bed are dark gray but grade vertically into green-gray shale as the amount of fossil fragments increases. These green-gray shales in turn grade vertically through a poorly cemented transitional layer into a fragmental shell calcarenite bed 3 in to 2 ft thick. The upper portion of the calcarenite bed becomes progressively better sorted, and the uppermost several inches are commonly well laminated. The upper surface of these calcarenite beds is usually flat, and the contact with the overlying shale of the next cyclothem is sharp and without gradation. The thicker (2 ft) calcarenite beds can be traced laterally into bioherms (4 to 5 ft thick) which probably formed mounds 2 or 3 ft high on the sea floor and were the source of the shell fragments. Away from the bioherms the calcarenite beds become progressively thinner, better sorted, and finer in grain size. Fragments of crinoids, brachiopods, fusulinids, echinoids, and bryozoans make up most of the calcarenite beds; they are cemented by sparry calcite. Only locally are siliceous silt and clay common constituents. The general lack of fine clay and silt in these beds suggests fairly strong current action and some degree of size sorting. The larger shell fragments were carried only a short distance down the flanks of the bioherms, but the smaller fragments were carried somewhat farther. The lower cyclothems have thick calcarenite tongues; associated bioherms are exposed along strike. In the upper cyclothems the calcarenites are thin, and only a few beds can be traced laterally into bioherms. As this sequence is transgressive over an erosional surface, the upper cyclothems are probably deeper water tongues of biohermal debris aprons.

At the base of the Neal Ranch Formation, the upper few feet of the underlying gray reefy limestone, bed 2 of King (1937), locally contain pebbles of biomicrite and biosparite-biomicrite derived apparently by erosion of this reef after it was lithified. Typical Wolfcampian fusulinids (*Triticites pinguis* Dunbar and Skinner and *Triticites koschmanni* Skinner) occur in these con-

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EXPLANATION OF PLATE 1

FIG. 1. Biosparite, sample 43-9; algal plate in upper left corner filled with coarse sparry calcite; clear grains are quartz; calcite crystals becoming smaller and grading into microcrystalline matrix in lower right corner.

FIG. 2.—Biosparite, sample 43-10; fossil fragments filled with a fine matrix which has recrystallized in part to sparry calcite; brachiopod spine in upper right corner retaining original wall structure is filled with sparry calcite similar to matrix; clear grains are quartz.

FIG. 3.—Biomicrite, sample 43-15; poorly defined fossil fragment near center; small mass of sparry calcite just above center, strongly cemented matrix shows little change in crystal size.

FIG. 4.—Biomicrite, sample 43-11; fossil fragments filled with sparry calcite and matrix having only a few well defined sparry calcite crystals.

FIG. 5.—Biomicrosparite, sample 40-20; algal plates filled with coarse sparry calcite in center and at right; fusulinid having microsparry calcite matrix at lower left corner; matrix of microsparry calcite that has interlocking boundaries with the algal plates.

FIG. 6.—Biosparite, sample 43-17; fossil fragments filled with sparry calcite; algal fragment at right filled with sparry calcite; and dark patch of organic material at bottom.

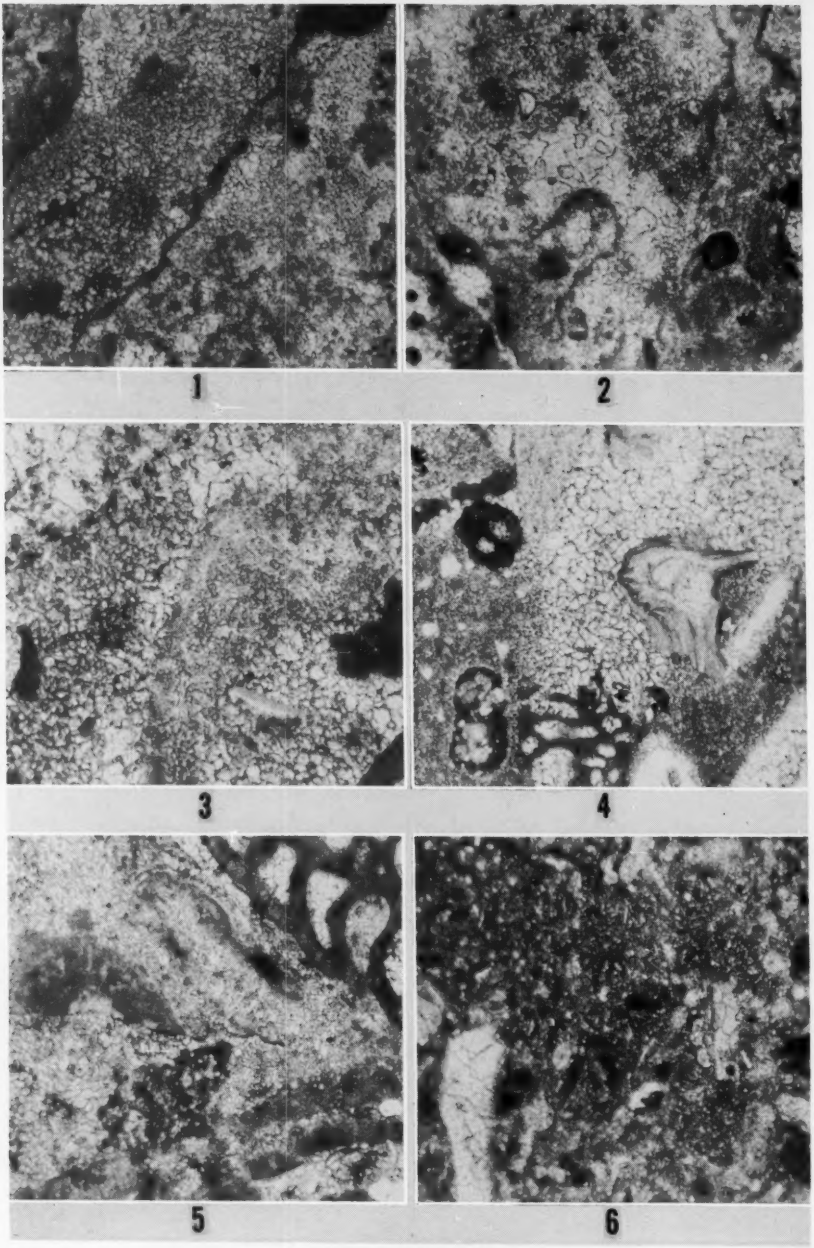

PLATE 2. Photomicrographs ×50

glomerate lenses and suggest these lenses are a "basal conglomerate" of the Neal Ranch Formation. Likewise the calcarenites in the lower 20 to 30 ft of the Neal Ranch Formation locally contain numerous pebbles of this light gray limestone and chert.

Samples from the lower, poorly sorted portions of the thicker calcarenite lenses (sample 22-7) are generally biomicrites and contain fragments of crinoids, bryozoans, echinoids, algal plates (recrystallized), and numerous fusulinids. Those from the upper, well sorted layers of these calcarenite lenses are biosparites, commonly with 5 to 10 percent quartz and chert constituents (22-9, 22-11, 22-13 pl. 2, fig. 3, and 22-24). Fragments of fusulinids, smaller foraminifera, brachiopods, and crinoid columnals form the major part of the rock, but recrystallized gastropods, algal plates, and stromatoporoids are locally common. Brown clay concentrated at the sparry calcite crystal boundaries suggests that much of the sparry calcite was formed from a recrystallized finer grained matrix (pl. 2, fig. 3).

The thinner calcarenite lenses, believed to represent deposition farther from the biohermal source are biomicrosparites and contain abundant fusulinids and crinoid columnals, and, in addition, a wide range of small fossil fragments and a few pebbles of older limestones (22-16, 22-20A, 22-22 pl. 2, fig. 5, and 22-26 pl. 2, fig. 4). Brown clay and silt and a very fine quartz sand are more common in these rocks than in the thicker calcarenite lenses, and algal fragments are very rare.

Lenox Hills Formation

The third sequence investigated is the type section of the Lenox Hills Formation (upper part of Wolfcamp Series) and the overlying lower part of the Leonard Formation in the southeast facing escarpment of the Lenox Hills, 7 miles northwest of Marathon (figs. 1 and 2C). The basal part of the Lenox Hills Formation is a limestone conglomerate approximately 150 ft thick, consisting dominantly of limestone cobbles and pebbles and having a calcite-quartz sand matrix. These beds rest with angular unconformity on folded and truncated shales, sandstones, and limestones of the lower part of the Wolfcamp Series and older strata. The upper strata of the Lenox Hills Formation at this locality are shale and fine pebble limestone conglomerate which are 125 ft thick. Within one mile to the southwest the upper shaly strata intertongue and pass into foreset conglomerate beds so that the entire sequence becomes conglomeratic. To the northeast the Lenox Hills Formation changes facies into biohermal limestones, and farther to the north·

EXPLANATION OF PLATE 2

FIG. 1.—Biosparite-biomicrosparite, sample 22A-1; Gaptank Formation, Wolf Camp Hills. Worm burrow filled with sparry calcite in left center; successive gradation of sparry calcite into microsparry calcite (center) passing into a darker microcrystalline matrix at far right.

FIG. 2.—Biomicrite, sample 22-1A; Gaptank Formation, Wolf Camp Hills, a local patch of sparry calcite grading at lower left into crystals forming algal fragment and at right into microcrystalline matrix.

FIG. 3.—Biosparite, sample 22-13; Neal Ranch Formation, Wolf Camp Hills; gradation of matrix of sparry calcite into microsparry calcite passing into microcrystalline matrix in the center.

FIG. 4.—Biosparite, sample 22-26; Neal Ranch Formation, Wolf Camp Hills; increase in size of sparry calcite crystals toward bryozoan and fusulinid fragments at lower center and right, and decrease in size toward clear quartz grains at left.

FIG. 5.—Biomicrosparite, sample 22-22; Neal Ranch Formation, Wolf Camp Hills, microsparry calcite matrix showing patches of sparry calcite; this suggests recrystallization of a finer microcrystalline matrix (left center) and sparry calcite filling of fusulinid test (upper right).

FIG. 6.—Biomicrosparite, sample 8-49; Leonard formation, Lenox Hills. Gastropod fragment (lower left) inverted to sparry calcite as are other fossil fragments (center, right); microsparry calcite matrix has organic material forming dark boundaries.

east near Gap Tank it changes facies into red beds and conglomerates. In the Lenox Hills the Lenox Hills Formation appears to have been deposited as deltaic foreset and bottomset strata.

The thin limestones of the upper part of the Lenox Hills Formation in its type section have many pebbles of older limestones and a terrigenous silt and clay matrix. Quartz and chert sand grains are abundantly scattered throughout, and fragments of gastropods, fusulinids, and crinoid columnals are the dominant constituents. Sparry calcite is common within fossil shell openings but does not generally cement the grains of the rock.

Lower Part of Leonard Formation

Overlying the Lenox Hills Formation disconformably and locally with angular unconformity are the basal limestone ledges of the Leonard Formation. These strata are lenticular, coarse calcirudites having a calcareous cement and containing a rich fauna of attached brachiopods, corals, specialized fusulinids, and large crinoid columnals between large blocks of older limestone and chert. Overlying and locally intertonguing with this basal unit are thin quartz sandstones, siltstones, and calcarenite lenses which are almost 40 ft thick (samples 8-25 and 8-27). The succeeding 80 to 90 ft are composed of shale, thin, fine grained quartz sandstones, and limestones (8-27, 8-40, 8-49 pl. 2, fig. 6). The top of this sequence is overlain by the First Limestone Member of the Leonard Formation of King (1937) which contains limestone and chert cobbles and pebbles in its basal beds.

The rocks in the lower 50 to 60 ft of this sequence suggest near shore, shallow water environments; in contrast, the upper part of the sequence is the beginning of a deeper water facies of the Leonard Formation.

The limestones immediately above the basal ledge of the Leonard Formation (8-25 and 8-27) are biosparites having occasional biosparite-biomicrosparite lenses. Fragments of bryozoans, crinoids, brachiopods, algae, stromatoporoids, and a few fusulinids are the main constituents of these limestones. Pellets (some with algal rims), limestone fragments, and quartz grains are minor constituents.

Samples 8-27 and 8-40 from the black fetid limestones of the upper part of this sequence are biosparite-biomicrosparites. In these samples, brachiopod fragments, crinoid columnals, fusulinids, and bryozoans are common, as also are quartz and chert sand grains. Sample 8-49 (pl. 2, fig. 6) is a biomicrosparite having only gastropod fragments (recrystallized) and very fine quartz sand grains. A black (hydrocarbon) material is dispersed throughout the rock between microsparite crystals.

EXPERIMENTAL METHOD

The experimental method used to obtain carbon 13/12 isotope data is applicable to all limestones. However, in our study of depositional and post-depositional environments, limestones of principally bioclastic origin were selected. Limestones formed of fragments of older limestones do not give a reliable isotopic representation of the environment of deposition at the time of their later redeposition, so that detrital limestones, or calcilithites (terminology of Folk, 1959), such as calcirudites are excluded from this study.

A rock specimen sufficiently large to represent adequately the various calcium carbonate constituents was powdered. From this powder a sample of 100 mg was treated with 50 percent phosphoric acid to release CO_2 from the $CaCO_3$. Greater concentrations of phosphoric acid may dehydrate organic material so that the resulting CO_2 may then arise in part from the breakdown of organic material as well as from the $CaCO_3$.

The liberated CO_2 was passed through a trap immersed in dry ice-acetone mixture and caught in a following trap which was cooled with liquid nitrogen. The CO_2 was sublimed through the dry ice-acetone trap two or three times to completely remove any moisture present. The pressure in the entire vacuum line system was maintained at 1 micron of Hg or less to keep incondensible atmospheric gases to a minimum. CO_2 in the sample flask usually had a pressure of approximately 100 mm Hg, and thus the impurities were less than 1 micron/100 mm (one part in 100,000). The vacuum in the line was maintained by a mercury diffusion pump through a trap cooled with

liquid nitrogen, and thus there was no appreciable contamination by atmospheric air or other gases.

The peaks at masses 44 and 45 of the resulting CO_2 were measured in a mass spectrometer of the double collector type, Consolidated Model 21-401. The peak at mass 44 represents $C^{12}O_2^{16}$, and the peak at mass 45 represents $C^{13}O_2^{16}$ and $C^{12}O^{16}O^{17}$. The $C^{12}O^{16}O^{17}$ component constitutes about 6.5 percent of the total mass 45 value (Craig, 1957a, p. 141), and this factor may be corrected by the following calculation.

1) $$\Delta C^{13} = 1.0676\Delta_m - 0.0338\Delta O^{18}$$

The mass spectrometer was calibrated using two standards: N.B.S. no. 20 (Solenhofen limestone) and N.B.S. no. 21 (Spectroscopic Graphite). Craig (1957a) calculated C^{13} abundances of 0.0112253 for N.B.S. no. 20, and 0.0109249 for N.B.S. no. 21, there being a difference of 0.0003004 between the two samples. For samples from the same two standards the mass spectrometer at Yale gave a difference of 0.000315; that was an exaggeration of mass difference by 30.04/31.5. Therefore in using the Yale mass spectrometer, in order to correct the difference, d, between a sample and N.B.S. no. 20, the equation

2) $$0.0112253 \pm \frac{30.04}{31.5} d$$

was used. For the belemnite (PDB-Chicago) used in the Chicago laboratory as a standard, Craig determined C^{13}/C^{12} as 0.0112372 and the parts per mil deviation from this Chicago standard and the sample determination at Yale were made by the equation:

3) $$\frac{\left(0.0112253 \pm \frac{30.04}{31.5} d\right) - 0.0112372}{0.0112372} \times 1000 = \delta ‰ C^{13}$$

The experiment was performed several times on each sample and the mass values were reproducible to $\pm 0.3‰$; for most samples this reproducibility figure was considerably less.

Oxygen 17 and 18 isotopes may be present in limestones and give false values to $\delta C^{13}‰$ (mass 45). Craig (1957a, p. 142) gives the range of δO^{18} as 30.0‰ which could give a false spread to the δC^{13} values of 1.0‰ (equation 1) for extreme δO^{18} values. Engel, Clayton, and Epstein (1958) show only 8‰ variation in δO^{18} values between contact metamorphosed limestone and non-metamorphosed limestone in the Leadville district of Colorado. Since the limestones under consideration have not undergone high temperature alteration, the variation in their δO^{18} values should not be as extreme as the range given by Craig, and the δC^{13} values were corrected only for the calibration differences using the N.B.S. no. 20 and no. 21 (equation 3).

INTERPRETATION

Calcium Carbonate Materials

To evaluate the physical and chemical properties of the limestones from the upper Paleozoic of the Glass Mountains it is necessary to analyze the origin of the many constituents. Of these constituents, the fossil fragments are organic in origin, the pebbles and coarse sand size fragments of older limestones are terrigenous in origin, the matrix of sparry calcite and microsparry calcite are preponderantly diagenetic in origin, and part of the microcrystalline matrix is possibly chemical in origin. Possible changes resulting from meteoric water percolation through limestones near the surface has not been taken into account. The significance of this factor is unknown. Our samples were taken from fresh, unweathered exposures.

The fossil fragments and pebbles and coarse sand size fragments of older limestones are readily identified as to source, but the matrix material poses many interesting problems. Sparry calcite is common in most of the limestones, although its abundance varies. There are two types, each distinctive and apparently different in its origin. One is aragonite, originally forming gastropod and pelecypod shells and algal plates, which has been recrystallized by inversion to a coarse clear sparry calcite. The other is the cement between fossil fragments and other clastic fragments which may originate in several ways. Folk (1959, p. 34) believed most sparry calcite represented pore fillings between sand size fragments. Pore filling is also certainly demonstrated in the voids of fossils which may commonly

have possessed only a small amount of original shell material. For example, in living echinoids the plates are a porous meshwork of calcite, and in a fossil echinoid perhaps only 40 percent of the volume of the plate is calcite which was secreted by the organism. The bryozoan skeletons are similarly about 35 to 40 percent original shell by volume. Fusulinids are an even more striking example, as the test in many species is probably less than 5 percent of the total volume of the shell. Thin section examination shows that the echinoid fragments, fusulinid tests, and bryozoan skeletons are filled with secondary calcite. Thus, the total amount of original shell material in many calcarenites is small. It would be interesting to analyze the shell material of individual microfossils, but no technique has yet been found whereby these micro shells can be cleaned of their secondary calcite fillings in order to be analyzed for the original shell $CaCO_3$. Likewise, the packing of medium to coarse sand sizes in calcarenite leaves many voids, but the porosity of these various limestones is low. Thin sections show the voids between grains to be filled with secondary calcite.

In biosparites there is commonly a complete gradation in crystal dimensions of the calcite cement from coarse to fine or very fine microsparry calcite. The calcite cement may be as coarse as that in shell voids or may be a microsparry calcite having gradational boundaries with the microcrystalline matrix (pl. 2, figs. 2, 3, and 4). The gradation in crystal size from sparry calcite into microsparry calcite and microcrystalline matrix, together with the segregation of brown clay at crystal boundaries (pl. 2, fig. 3), suggest that the introduction of coarse pore-filling sparry calcite was attended by recrystallization of the fine matrix originally deposited in the calcarenites.

Microsparry calcite is common in several rock types, principally in biomicrosparites (pl. 1, fig. 5) and biosparite-biomicrosparites (pl. 2, fig. 1). These rocks commonly contain significant numbers of algal plates and fragments which were originally aragonitic. During diagenesis the aragonite in these fossil fragments inverted to calcite. At the same time, apparently, the fine grained matrix changed to microsparry calcite as shown by interprenetration of crystal boundaries (pl. 1, fig. 5). This suggests that much of the original matrix in algal limestones may also have been aragonitic and that the matrix may represent fine calcium carbonate precipitated in algal wall tissue which was released when the plant died (Fogg, 1953, p. 35).

The microsparry calcite forming the matrix in the dark gray to black limestones from the basin facies (pl. 2, fig. 6) is of uncertain origin. The calcite crystals are unequal in size, and they grade into small patches of coarse sparry calcite, some of which are recrystallized gastropod shell fragments. The matrix seems to represent fine shell fragments deposited in a restricted or reducing environment.

In a few limestone samples collected from resistant beds, sparry calcite is almost completely lacking (pl. 1, fig. 3). In these, microcrystalline matrix forms the dominant part of the rock, and it appears that these strongly cemented limestones result from recrystallization of the original clay and silt size calcite fragments. Several of the recrystallized aragonitic fossil fragments in these rocks are composed of sparry calcite which, near the fossil boundaries, becomes microsparry calcite before passing into a microcrystalline matrix (pl. 1, fig. 3).

Carbon Isotope Distribution

Recent marine shells do not have the complex diagenetic history that is common in fossil fragments, and the distribution of C^{13} and C^{12} in the Recent marine shells is taken as a starting point. The determinations by Craig (1953, p. 62; 1957b, p. 270–271) indicate the range of C^{13}/C^{12} isotope variations in Recent organisms. He showed that in foraminiferal tests the δC^{13} values range between $+1.2$ and $+1.9$, whereas in the Asteroidea the values reach approximately -5.9 and in the Echinoidea -3.5. In pelecypods the δC^{13} values vary widely from -3.8 to $+1.8$, and in the Zoantharia (Coelenterata) they are about -1.4.

The Recent marine aragonite algae are rich in C^{13} and the δC^{13} values range between $+3.1$ and $+4.3$, whereas in calcitic algae (corallines) the δC^{13} value is -4.5.

Thus, in Recent organisms the variation and distribution of the stable carbon isotopes is still very incompletely known, but sufficient data is available to permit limited interpretation.

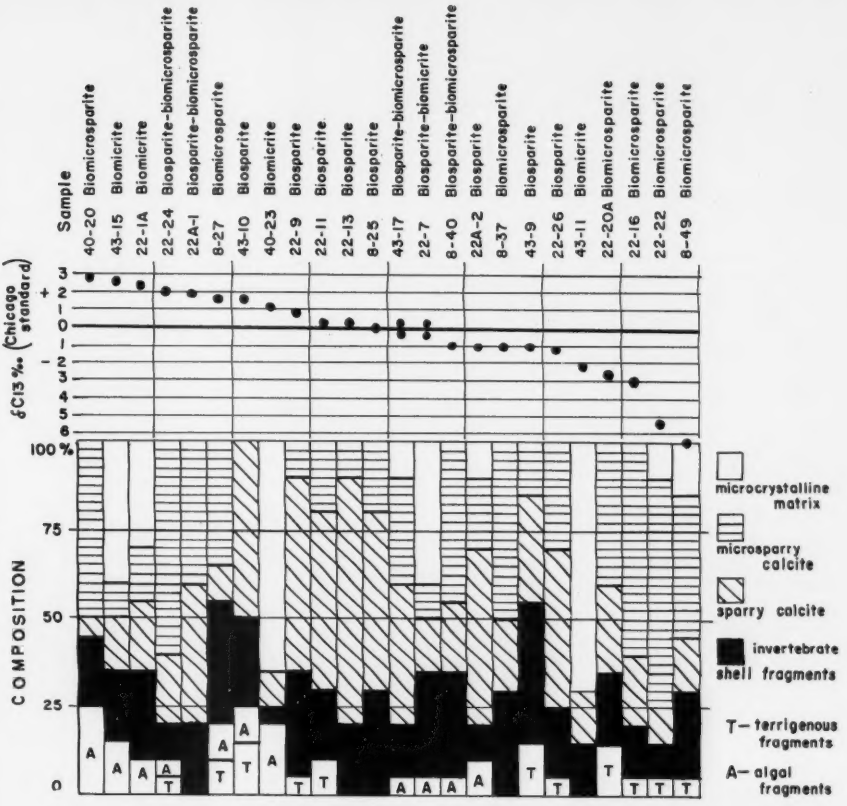

FIG. 3.—Relations between C^{13}/C^{12} ratio in limestones having varying amounts of fossil fragments, sparry calcite, microsparry calcite, and microcrystalline matrix.

In contrast to the carbonate history of individual Recent marine shells, which is influenced primarily by environment, the history of a limestone is complex, and many opportunities exist for the interchange of calcium carbonate as a result of recrystallization and cementation. Also, analysis of a limestone includes a multicomponent system of an assemblage of fossil fragments, whereas Recent shells can be analyzed separately.

Several studies have touched upon the problems of limestone environments and carbon isotope ratios. Landergren (1953, p. 100–101) showed a relation between oxidizing and reducing environments (based on color) and carbon isotope ratios and suggested (p. 116–119) that in reducing environments C^{12} increases as a result of contribution from organic decay in water surrounding the growing organism. Jeffery and others (1955) studied approximately 100 limestone and coal specimens from Australia and found considerable variation in carbon isotopic composition. They believed environmental, depositional, and diagenetic processes play an important role in the final carbon isotopic composition of a limestone, but they apparently do not agree with Landergren's interpretation that there is a correlation between oxidation state (based on color) and the isotopic composition but

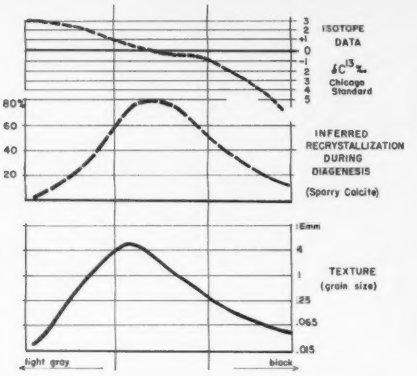

FIG. 4.—Interpretation of the relations between carbon isotope data, inferred amount of recrystallization during diagenesis, and the texture (grain size) of the original particles of the calcareous sediment.

would recycle carbon isotopes during world wide orogenic pulses.

Clayton and Degens (1959) found that Pennsylvanian marine limestones are considerably richer in Carbon 13 ($\delta C^{13}‰$ mean = 1.54) than Pennsylvanian nonmarine limestones ($\delta C^{13}‰$ mean = −6.66) and believed this difference is a criterion for distinguishing between the two types of limestone.

Craig (1957b, p. 275) showed that carbon isotope composition in marine shells does not follow a paleotemperature scale as does O^{18}, but in chemically precipitated calcium carbonate in thermal springs, a temperature relation of the carbon isotope composition does exist (Craig, 1957b, p. 275; McCrea, 1950).

Wickman, Blix, and von Ubisch (1951) suggested that C^{13} enrichment of secondary calcite in Silurian reef limestones may be the result of CO_2 derived from organic decay which enters into the precipitation of the secondary calcite.

In the light of our own data, comparison of the particle composition and the δC^{13} values of the limestones from the Pennsylvanian and Permian, Glass Mountains, shows several significant trends (figs. 3 and 4). Generally, samples of biomicrosparites or biomicrites have either distinctly positive or negative δC^{13} values, and only two limestones of these two types approach zero, that is, a C^{13}/C^{12} ratio equal to the standard, Chicago PDB, a belemnite. In biosparites having a large amount of sparry calcite, the δC^{13} values lie between +1.0 and −1.0. As the amount of sparry calcite decreases, the δC^{13} values become either more positive or more negative.

Thus, these observations suggest that limestones which have undergone little recrystallization have a wider spread of δC^{13} values than do limestones which show evidence of considerable recrystallization or introduction of calcite cement (fig. 4). The effect of recrystallization is apparently to shift the δC^{13} values toward the range of +1 to $-1‰$ and thus also toward the value of the belemnite standard. Does this suggest that the belemnite standard was recrystallized or does it suggest that the belemnite calcium carbonate was in isotopic equilibrium with sea water?

Several additional features of carbon isotopic distribution are worthy of consideration. Sea water bicarbonate has δC^{13} values of about −1.2 to $-2.9‰$ (Craig, 1954, p. 136), and the enrichment of C^{13} in a crystal lattice precipitated from a bicarbonate solution is $3.8‰$ at 25 degrees C (McCrea, 1950). Also Oana and Deevey (1960, p. 261) have found that gas from the Yamagata gas field of Japan has CH_4 having δC^{13} values averaging $-71.6‰$ and associated CO_2 having δC^{13} values averaging $-6.9‰$ and can be as high as $+2.0‰$, which they believe to result from equilibrium fractionation during methane fermentation of organic material by bacteria.

It seems likely, therefore, that the complicated process of limestone cementation involves the introduction of $CaCO_3$ into pore spaces by connate water, with associated solution and recrystallization of the fine $CaCO_3$ particles originally present in the calcareous sediment. Connate water would have a replenishing supply of CO_2 and δC^{13} values of approximately $-6.9‰$ or higher, resulting from bacterial decomposition of organic material. Additional Ca^{++} ions could be derived from dissociation of Ca^{++} in clay minerals occurring in the interbedded shale lenses.

Biomicrosparites and biomicrites having

abundant fossil flora present as algal fragments show distinctly positive δC^{13} values; this feature is in agreement with the positive δC^{13} values determined in analyses of Recent algal plates, whereas no relation could be observed in the variation of the δC^{13} values and the abundance of particular types of invertebrate fossil fragments in the limestone samples.

Samples of light gray limestone generally have positive δC^{13} values greater than $+1.0°/_{oo}$, and samples of dark gray or black limestone have negative δC^{13} values less than -3.0. Since these two rock types are usually biomicrites or biomicrosparites, little pore filling by $CaCO_3$ is suggested, and the δC^{13} values have probably been only slightly altered during diagenesis. The light gray limestone was probably formed in an oxidizing environment and the dark gray or black limestone in a reducing environment. If the reducing environment included bicarbonate ions which have low δC^{13} values, perhaps from incomplete equilibrium fractionation of CO_2 and CH_4 in methane fermentation, the dark colored limestones may be accumulations of shell fragments that originally contained less C^{13} than the light colored limestones which were formed in the better aerated, oxidizing environment where sea water had a normal abundance of C^{13}.

Based on the C^{13}/C^{12} ratios and the composition and texture of the limestones, several implications are noted. One is that most coarse sparry calcite is either calcite introduced into pores in the original sediment or that it results from solution and redeposition of calcite essentially in place. In both processes isotopic equilibrium with interstitial solutions could be achieved. This indicates that coarser grained limestones, such as biosparites, are more strongly affected by post-depositional processes than the biomicrosparites. Microsparry calcite suggests recrystallization and apparently limited introduction of carbonate from outside sources; thus biomicrosparites have been more extensively recrystallized than finer grained biomicrites.

Porosity and permeability of the limestones thus control the changes in C^{13}/C^{12} ratios by limiting the amount of additional carbonate which is introduced.

CONCLUSION

The clastic limestones of these late Pennsylvanian and early Permian strata record a complex history of deposition and diagenesis from which the depositional environments may be reconstructed. The various limestones characterizing different facies can be readily recognized in the field although they have resulted from depositional environments having many complex physical and chemical controls.

In the late Pennsylvanian Gaptank Formation the thick shallow water reef deposits are mainly biomicrites and biosparites having a high percentage of algal fragments and showing an enrichment of C^{13}. In the early Permian Neal Ranch Formation the shallow water patch reef deposits extend locally into aprons of shell fragments deposited in more poorly aerated water. They are mainly poorly sorted biosparites, and the high percentage of sparry calcite cement suggests a significant introduction of calcium carbonate from outside sources. These rocks show the greatest range of C^{13}, $+1.0$ to $-5.5°/_{oo}$.

The texture and particle constituents, as shown by field relations and thin section studies, reflect in varying degrees their environmental, depositional, and diagenetic history. The environment of deposition and diagenetic history of the limestones seem to be the best guides to the carbon isotope distribution in carbonates.

ACKNOWLEDGMENTS

We thank R. D. Stevens, Isotope and Nuclear Research Laboratory, Geological Survey of Canada, and June Phillips Ross, Illinois State Geological Survey, who critically read the manuscript and offered many valuable suggestions.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 31, NO. 2, PP. 245–255
FIGS. 1–6, JUNE, 1961

MARINE AND LAGOONAL DEPOSITS IN CLAY DUNES, GULF COAST, TEXAS[1]

W. ARMSTRONG PRICE[2] AND LOUIS S. KORNICKER[3]
Institute of Marine Science, The University of Texas, Port Aransas, Texas

ABSTRACT

Thin, light-weight valves of *Mulinia lateralis*, a lagoonal clam, are found evenly and naturally interbedded in clay at 8 to 33 ft above mean sea level in a clay dune of the mainland shore of Laguna Madre, the coastal lagoon of southwestern Texas. The dune is on the lee shore of a small embayment where the shells seem to have been carried from the parent lagoon by waves and currents and strewn on a mud flat normally barren of subaqueous invertebrates. The shells were then redistributed by wind over the dune. Previously, the only fossils reported from clay dunes have been foraminifera and food animals and shells of aboriginal camp sites.

The environment of the occurrence is briefly described, with a review of the origin and development of clay dunes. An irregularly distributed layer of organic and inorganic flotsam deposited on the clay dunes by storm waves is also described, and it is concluded that the *M. lateralis* shells were not similarly deposited.

INTRODUCTION

The presence of clam shells naturally interbedded in ancient sediments is usually considered as evidence that the enclosing sediments were deposited in a subaqueous environment. Alternating beds of clam shells and clay is a typical marine or lagoonal sequence. Therefore, when the occurrence of shell layers (not of aboriginal midden origin) in a clay dune formed subaerially near Port Isabel, Texas, was brought to the attention of the authors, it seemed worthy of further investigation.

This paper describes briefly the primary and secondary sedimentary features observed during a reconnaissance of the area near Port Isabel and discusses their origin. Hurricane flotsam distributed on the clay dunes is also described, and the time of deposition estimated.

LOCATION

A very shallow three-pronged lagoonal indentation lies along the western shoreline of the Laguna Madre between Holly Beach at the north and Laguna Vista at the south, both being small communities on the eastern Laguna Madre shoreline, in Cameron County, Texas, 8 to 10 miles northwest of Port Isabel. The small lagoon—here called Rio Vista Lagoon—lies 2 miles north of an east-west stretch of State Highway No. 100 between San Benito and Port Isabel (fig. 1).

Features investigated were four clay dunes along the north and east shores of the lagoon. To facilitate description, the dunes have been designated D1, D2, D3 (Loma de la Grulla), and D4 (fig. 2).

RECENT PRE-DUNE GEOLOGY

Two elevated distributaries of a Recent subdelta of the Rio Grande (Los Fresnos Subdelta), earlier than the present Port Isabel Subdelta, when active flowed westward into the Gulf of Mexico 10 to 15 miles southeast of Rio Vista Lagoon (figs. 1 & 2). One of the distributaries, Holly Beach Resaca (a Spanish word for valley) passed north of Rio Vista Lagoon, and the other, Resaca Santa Ysabel (A. E. Anderson manuscript names), passed south of it (fig. 3). Holly Beach Resaca was eroded out and its course crossed west of Rio Vista Lagoon by the younger Resaca Santa Ysabel. A fragment of a distributary older than either of the preceding (see Old Resaca, fig. 3) formed a curving ridge west of the present Rio Vista Lagoon separating it from a depression to the west now occupied by a small

[1] Manuscript received May 16, 1960.
[2] Consulting Geologist and Oceanographer, Corpus Christi, Texas; Honorary Associate, the Institute of Marine Science, University of Texas, Port Aransas, Texas.
[3] Present address: Office of Naval Research, Tenth floor, 86 E. Randolph Street, Chicago, Illinois.

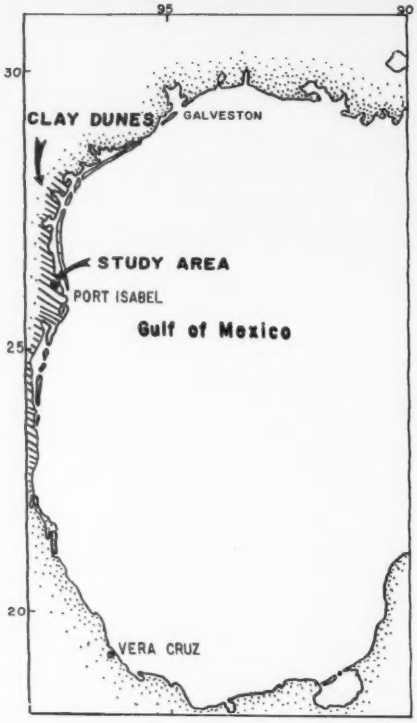

FIG. 1.—Map of Gulf of Mexico showing study area and area within which the clay dunes occur.

playa. The levee tops flanking the slightly winding distributary channels have slopes of about 1 ft/mi, as is shown by their gradients on the 1-ft-contour map (fig. 2). The flanks are somewhat steeper. The east-west trough between the distributaries slopes to the east. When the Rio Grande shifted south towards Mexico, playa lakes formed in the troughs when the climate became dry. The abandoned delta flank probably began to tilt slightly gulfward soon after the river left it. The eastern playas became flooded when the sea rose, probably about 4500 years ago. At that time the mainland delta shoreline became recessed by drowning and erosion to a maximum distance of 8 miles from the present outer shoreline (Price, 1958, p. 57) and a total distance of 25 miles from its furthest offshore limits (Price, 1954, p. 93, fig. 9). The invasion of the front of the Los Fresnos Subdelta has been gradual and may not have ended. Clay dune building began when the more pluvial climate of the period of low sealevel (late glacial) was succeeded by a dry climate probably about the time the present stillstand began. Erosion of the present delta front has been contemporaneous with the clay dune history, the sites of active dune building retreating as lagoonal shores were bluffed.

ORIGIN, HISTORY, AND DISTRIBUTION OF CLAY DUNES

Clay dunes are even-topped, ridge-shaped eolian deposits limited to the shores of clay-floored saline playas and tidal mud flats. They are numerous in the warm parts of the dry climates—dry subhumid to semiarid. Some clay dunes occur in fully arid regions. They have been recognized under various names in the Americas, Africa, and Australia. In Australia somewhat inactive crescentic clay dunes of Victoria have been described as lunettes (Hills, 1940). The dune slopes are low and the surfaces smooth except where they are bluffed or gullied, as are many in the Rio Vista area.

Clay dunes—with a high percentage of calcareous clay—are distributed along the mainland coast of the Gulf of Mexico from Rancho Tepehauje (23° 30′ N. L.) 15 miles south of the mouth of the Soto la Marina River, in Tamaulipas, to the middle of St. Charles Bay, Texas (28° 13′ N. Lat.) (fig. 1). The dunes are highest (to 35 ft) in the Rio Grande delta, becoming lower (3-ft minimum) toward the more humid climates at the north and south. Clay dunes have been described in some detail from Texas (Coffey, 1909; Price, 1933, p. 932–935, figs. 8, 10[4]; 1958, p. 56–59; Huffman and Price, 1949) and Australia (Stephens and Crocker, 1946).

Dunes of clay form because under strong, steady on-shore winds in the warm-to-hot seasons with strong insolation, the surface of a drying, saline mud flat breaks down into particles of sand size and smaller, with small grains of evaporite crystals. Dessicated

[4] Fig. 12, purporting to show clay dunes, shows mixed assemblages of dunes, including sand dunes.

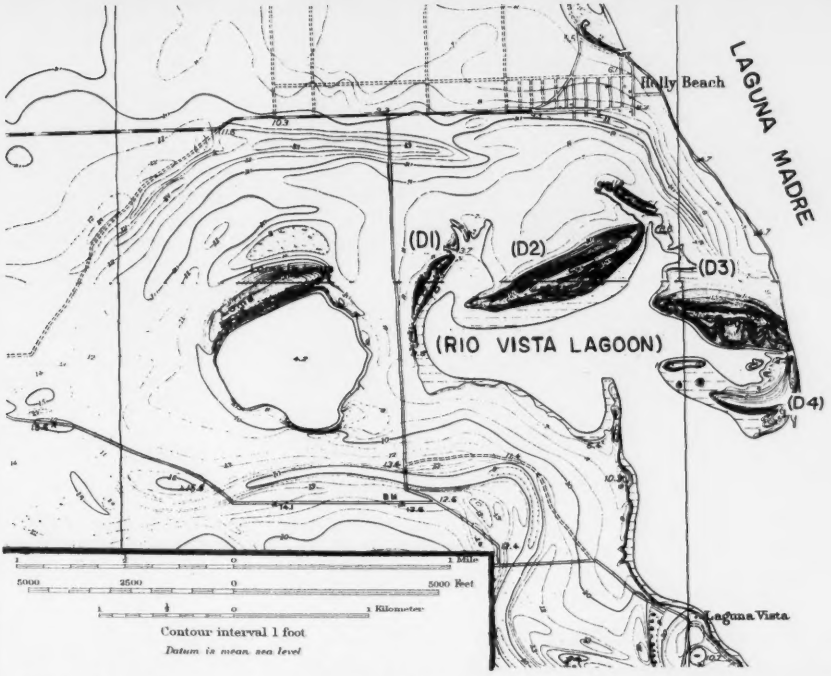

FIG. 2.—Topographic map of study area (Rio Vista Lagoon and clay dunes) from United States Department of Interior, U. S. Geological Survey, topographic maps of Cameron County, Texas. Contour interval 1 foot. Datum is mean sea level. True North vertical; approximate mean declination 9°. The name Rio Vista Lagoon and the designation of clay dunes as *D1, D2, D3,* and D4 have been added by the authors. Note gullies and cliffs on south side of dune D3.

algal growths may add organic matter to the accumulations. The flats are those of intermittent lake shores and the shores of tidal lagoons having little or no regular daily tidal range. Two phases of deflation of the flats are recognized, a phase in which mud-crack polygon laminae break down when separated from the flat by wind as the particles are transported to the shore and a phase in which the flats sediments become granulated by the formation of evaporite crystals. The sand-sized pellets are aggregates of quartizitic sand and silt in an envelope or with a matrix of lutitic sediment. A dust cloud often envelopes the flat and dune. The lutitic aggregates break down into dust by the time the transported eolian particles reach the rear border of the dune.

The eolian materials accumulate against the rising ground along shore and in obstructions such as trash-lines (flotsam) and vegetation. During moist nights after windy days, the windrows of initial dune growth take up moisture and the accumulations become temporarily plastic. The dry interiors of the dunes, although having some cohesiveness, retain a loosely porous structure, the clay seeming not to regain its initial compactness by 50 to 60 percent, nor its original structure so long as saline materials are being added to it. A granular structure may be induced in the coastal clays by soaking in brine, the clay shrinking and cracking. Whether any change in the clay molecules takes place in the saline environment has not been investigated.

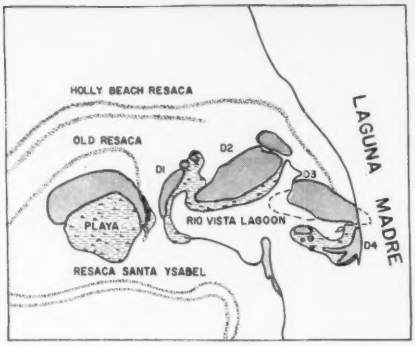

FIG. 3.—Map showing position of pre-dune deltaic distributaries (resacas) relative to present day clay dunes. Dashed line on east and west ends of dune D3 indicates probabe extent of dune before erosion.

The clay dunes of the western Gulf Coast grow only in the warm-to-hot months from March to October or November. Minor surface reworking may occur during winter droughts. Segregation of sand by rain causes a lamination of reworked dune material deposited along the edge of the flat. The dunes accumulate under warm-weather winds varying here from ENE through SE to SSW. The dunes are limited to shorelines that face these directions and all are, or have been, bordered by low flats containing more or less lutitic material. Where the sediment of the flats grades laterally or has varied in time from clay to sandy clay or clayey sand, the dune form varies toward that of a stabilized sand dune, some large interior dunes and some coastal ones being of a borderline type. As little as 8 percent of lutite is known from Australian examples to furnish enough plasticity to stabilize a clay dune without other fixing agents. Some of the interior sandy and gypsiferous clay dunes of Texas and some lagoonal accumulations containing some clay grade into eolian beach ridge and eolian beach plain forms but are limited to shores that face, or once faced, drying winds.

Clay dunes normally have only slight (intrazonal) soil zonation. The soils of dunes cut off from accessions of salty sediment by invasion of a deltaic distributary or in some other way may become fully zoned. Clay dunes are mapped in county reports covering the Rio Grande delta as Point Isabel clay and the saline flats as Lomalta clay. Sandy lee dunes of more interior coastal prairies which are related to clay dunes are mapped as Brennan soil. In Algeria, the clay dune and flats materials have been identified as a solonetz "soil" (Boulaine, 1956).

The dune-like structure of clay dunes is shown by their subdued cross-bedding and the progradation of large complex dunes toward the flats with one or two lesser, younger summits built against eroded or partly eroded surfaces of the original dunes. The late Recent age of the dunes in Texas is shown by (1) their continuing growth, (2) the absence of beveled and unconformable surfaces other than the inclined surfaces between prograding increments, (3) their 25- to 35-ft elevations where an approximate growth rate of about 0.5 to 1.0 ft per century has been estimated, and (4) by resting on late Recent sediments and topographic forms. These include: (a) the flanks, summits and eroded surfaces of Recent natural levees of deltaic distributaries, (b) banks of lately abandoned courses, (c) the sides of stream valleys entrenched in late Pleistocene time and (d) such shoreline features as small Recent creek deltas (Arroyo Colorado delta) and compound spits. Dunes bored through by Price and a few artificially excavated are seen to rest on Recent and Pleistocene beds, as at the Mud Bridge site, Airline Road crossing, Oso Creek, Corpus Christi. Completely buried clay dunes have not been recognized. Some dunes along the shores of the southern Laguna Madre are based slightly below sea level, either having sunk into older deposits by their weight or having originated before sea level reached its present level. The maximum exposed heights of coastal clay dunes, 35 ft along the Rio Grande, 27 at Corpus Christi, represent some 4500 to 5000 years of growth since the beginning of the present stillstand of sea level (Curray and Shepard, 1959; LeBlanc and Bernard, 1954).

Clay dunes were attractive camp sites for the fishing Indian tribes of the Texas coast. Two cultures have been recognized in them at Corpus Christi, an archaic culture and a late culture extending into early historic

time—the culture of the Karankawas. The extensive midden strata contain large bleached bay shells—clams, oysters, and snails—some with contained or adhering small-sized lagoonal organisms, also remains of land snails and vertebrate food animals besides flint, shell, bone, and pottery artifacts. Naturally deposited fossils observed are limited to foraminifera (Price, 1934), land snails, and the thin Rio Vista molluscan layers to be described.

The net growth rate of clay dune summits is difficult to determine. Some data give a rate of 0.5 to 1.0 ft a century. In the Rio Grande delta and on Oso Creek, Corpus Christi, the archaic aboriginal artifacts (Aransas focus equivalents), lacking pottery and arrow points, extend from about the mid-heights of many dunes upward to about 4 ft below the pre-1940 summit surfaces. The upper 4 ft of 1940 contain the late culture materials (Rockport focus equivalents) with pottery, small arrow points, and, at the top, European materials including copper, iron, and deeply weathered and patinated glass bottle necks. The upper 1 ft in some 1940 dunes and some small lenses and summits in front of old dunes, lack aboriginal artifacts, the Indians having left the shorelines about 1850. The upper aboriginal culture dates from at least 1700 to 1850 and may be as early as 1500 A.D. During the 7-years drought of 1950 to 1956, some dune summits accumulated a foot or more of loosely consolidated pellet-clay and dust, now being eroded. A dune 14 ft high on a playa at the eastern side of Alazan Bay, an arm of Baffin Bay of Texas, contained an artifact layer 7 ft below its top in 1947. Taken from this layer were flint points of archaic type, a flat, bored greenstone gorget of a type found on the western coast of Mexico, a large orange-colored cobble stone, and a small carved greenstone figurine of a style of about 0 to 300 A.D. They seem to belong to the La Venta horizon.

CLAY DUNES OF RIO VISTA LAGOON

Dunes D1, D2, and D3 near Port Isabel may have started when the present Rio Vista Lagoon was a playa enclosed by the Holly Beach Resaca, the dunes accumulating along the northern and northwestern shores of the playa. However, Laguna Madre soon entered it. Dune D3 was formerly at least 0.1 to 0.25 miles longer at each end (fig. 3), judging by the slopes of its summit. Substantial erosion of dune D3 is shown by the steep bluffs on the eastern and western ends and the deeply gullied south face (fig. 2). After the Laguna Madre had entered the Laguna Vista, the low dune D4 developed on a compound spit formed by shoreline erosion of D3 and sediment drift from the north. The spit axis shifted,with growth, from west to southwest and is now growing to the south. Dune D4 rises to summits only 3, 9, and 12 ft high, whereas the much older dune D3 has summits rising to 30 and 34.6 ft above mean sea level.

No artifacts, aboriginal or historical, were found bedded in the dunes of the Rio Vista area. None of the large shells of the kinds found in middens were seen in or on these dunes. A single fragment was found on the mud flat.

INTERBEDDED SHELL LAYERS IN DUNE D3

Shell layers, each about $\frac{1}{4}$-in thick, interbedded with dune clay, were exposed in a zone about 2 ft thick 30 ft above mean sea level near the top of dune D3, on the southwestern face near the western end (fig. 4). A thicker level shell layer is exposed in the east bluff facing Laguna Madre and dips down the south flank along a road at the eastern end of dune D3 (fig. 2). Throughout the exposures the shells consist mostly of disarticulated valves belonging to the clam *Mulinia lateralis*, a species now living in large numbers in the Laguna Madre. *Mulinia lateralis* is a small clam growing to a length of about $\frac{1}{2}$-in at maturity. The shells in the layers were somewhat smaller than this and many were fragmented. They were densely packed and oriented predominantly with the concave side facing down. No large shells of other species were observed, but a few juveniles less than $\frac{1}{2}$-inch long which belong to species reaching several inches at maturity were in the shell layers. The bed at the east end of dune D3 is 8–10 ft above mean sea level and dips north and south with the normal dune stratification. *Mulinia* shells of dune D3 seem to be the first definite marine (lagoonal) shells larger than foraminifera and not of midden origin to be reported from clay dunes.

The interbedding of the shell layers in the clay dune suggests that they were accumulated by wind, especially since the attitude of the shell beds coincides with the normal dune stratification. Although the shell layers in dune D3 strongly resemble those usually associated with subaqueous sedimentation, they were evidently deposited subaerially by moderate or strong winds.

In order to test the competence of wind in transporting *Mulinia lateralis* up a slope, the following experiments were performed. A broad, smooth board 7 ft long was adjusted so that the angle of its plane with

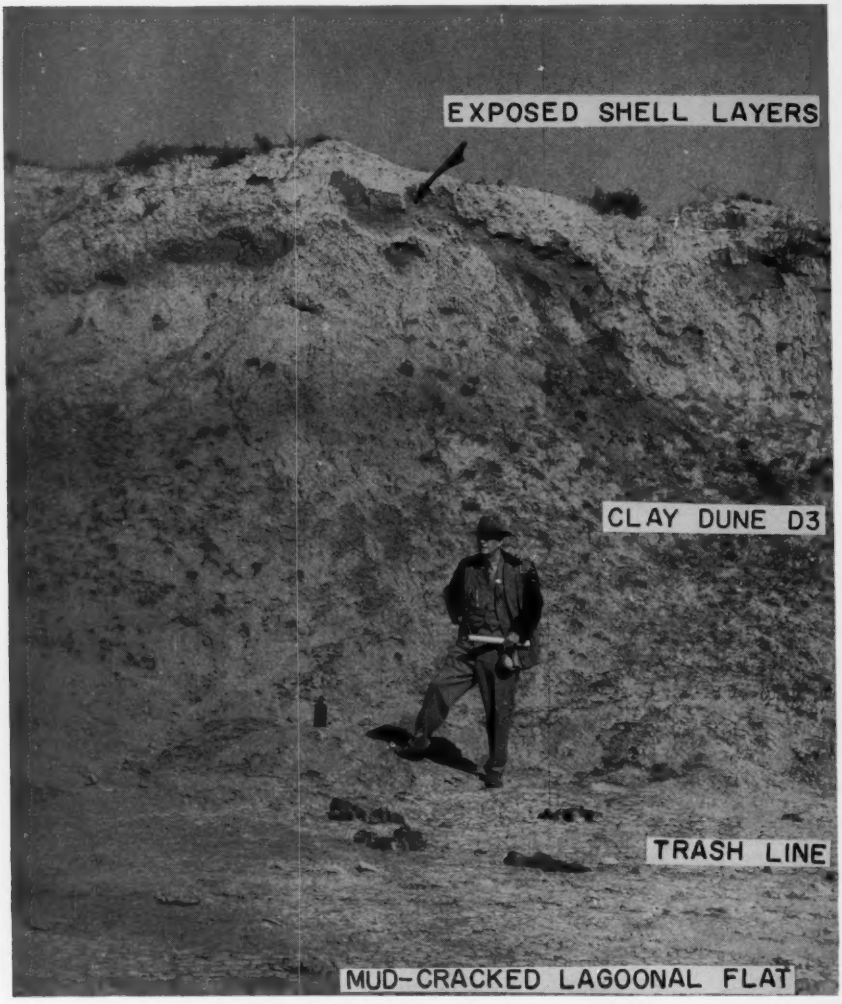

FIG. 4.—Cliffing near west end of south face of dune D3. Position of shell layers exposed near top of 30–35 ft dune are marked by arrow. Flotsam on flat with a bottle placed on end by the observers.

the horizontal could be varied. The inclined board was then placed outdoors in a position where its lower end faced a strong wind. The wind velocity was measured at 20 mph with a hand anemometer held near the base of the board. The behavior of *M. lateralis* shells dropped onto the bottom of the board was observed when the angle of its plane with the horizontal was 15°, 30°, and 45°. Shells of *M. lateralis*, and especially fragmented ones, were blown up the board at all angles tested. A few unbroken shells, oriented with the concave side down, remained on the board. These experiments show that winds of moderate velocity for the coast of Texas are capable of transporting small shells, similar to those found interbedded in dune D3, up a smooth surface.

The concave-down position seems to be the stable attitude of shells transported by wind as well as by water. Large shells of *Dinocardium robustum* weighing up to 50 gm were observed to turn from the concave-up to the concave-down position during strong winds on the beach of Mustang Island, Texas.

The altitude of the shell beds above sea level, as well as their dip, would suggest a local tectonic movement in the area, if the shell layers were interpreted as having been deposited below water. The even topography of the summits and flanks of the deltaic distributaries on and against which dunes D1, D2, and D3 lie shows that the surface deposits have not been disturbed by faulting or local warping since their deposition. This is considered as additional evidence that the shell layers were deposited subaerially.

PROBABLE SEQUENCE OF EVENTS IN DEPOSITION OF THE CLAM SHELLS BY WIND

It has been concluded that the dune D3 shell layers are of eolian origin. However, the seeming absence of such shell layers in clay dunes, except here, indicates that lagoonal mollusca can probably not live on the source flats of clay dunes, or if they ever do, that they probably cannot grow there in sufficient quantities to form layers spreading up the foreslope and over the summit of the dune, a distance usually of several hundred feet. Hence, some very unusual condition or mechanism is indicated. Such a mechanism may exist at the mouth of the Rio Vista Lagoon in the compound spit of dune D4. Just this combination of lagoon orientation, spit position, and shell occurrence may be rare. This mechanism would have been able to operate only as and after the waters of Laguna Madre—the large coastal lagoon—invaded the former inter-meander basin, creating the small tidal Laguna Vista lagoon.

On many shores of Laguna Madre, as, for example, the shores of Bird Island in the northern Laguna Madre (Price, 1958, pl. III, fig. 1), there are low beach ridges of small lagoonal shells in which *Mulinia lateralis* is abundant. We may, then, postulate that the low, narrow shore flat of the bluffed shoreline north of and including D3 may have at times had a small beach of shells and shell fragments with *M. lateralis* shells common. Winds from northerly and easterly directions would develop waves and a longshore sediment drift that might carry the shells and beach development southward along the shoreline of the spit and westward into the Rio Vista Lagoon. Such shell deposits might then be driven northward toward the flat of the D3 dune and spread over it by waves and currents acting at storm sea levels. Only moderate wave action and low floods, such as may be caused by lesser gales, would be required. After waves driven by the strong north winds of winter had moved shells around the curve of the spit and spread them on the flat during the accompanying wind tide, the strong on-shore SE winds, beginning in March, and initiating eolian clay dune activity for the year, could have blown such light shells up onto the dune. Afterward, eolian clay deposition would cover the shell layer.

This sequence of events would explain the early low deposition of eolian shells on D3 toward the east and the appearance of shells later at the west at higher levels in lesser numbers and smaller sizes. These shells, 30 to 34 ft up in the dune, would have had to travel much farther up the dune flank from the source flat than would the shells at 10 ft at the eastern end, also promoting size differentiation. The flats of the Rio Vista Lagoon contained no shells when visited in the winter of 1960.

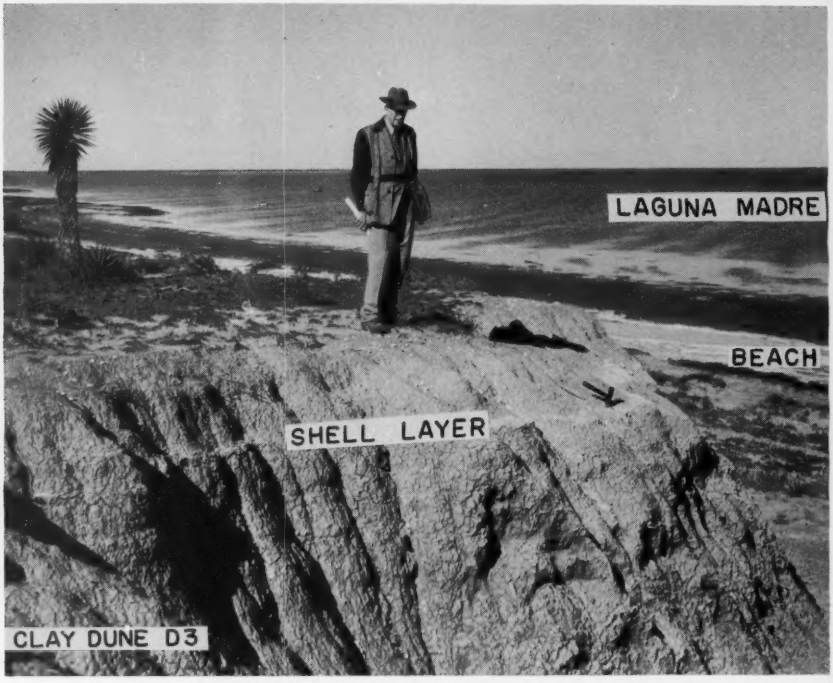

FIG. 5.—Shell layer exposed along east end of dune D3. Shell layer is marked with geological pick. Laguna Madre in background.

HURRICANE FLOTSAM

Objects interpreted as hurricane flotsam were observed in a narrow zone on the windward slopes of dunes D1 and D3. These objects included asphalt lumps, coral fragments, tropical beans, small lumps of wax or gum, pumice, scoria, slag or cinder, bottles, and timber. Shells were absent. All the material in the flotsam zone was sufficiently buoyant to be easily transported by water. The flotsam is evidently a surface deposit as none was found in place in the sides of deeply eroded gullies. Similar zones are common features in the backdune sand dunes area of Padre Island and mark the edge of high storm waters (fig. 6).

At the time of this study (January, 1960) the Rio Vista Lagoon contained little water, and strewn over the surface of its broad northern mud-flat at about 1 ft above mean sea level was a light accumulation of bottles, wood, some pumice, and mats of seaweed, all of which had remained after the withdrawal and evaporation of the water. This low flotsam had probably been derived mostly directly from the Gulf of Mexico, finding its way into the Laguna Madre through the Brazos Santiago Inlet, which is only 9 miles south of the Rio Vista Lagoon. High storm waters probably pick up flotsam previously deposited on the barrier islands as well as flotsam that accumulates in the lagoon during normal water levels and redistribute both at high levels. The height above mean sea level at which flotsam is deposited during a cyclonic storm on this coast depends on the strength, duration, and fetch of the wind, the heights and "drive" of the waves, the configuration of the shoreline of deposition, and on the time that the storm center takes to cross the Gulf of Mexico. The more slowly and the

FIG. 6.—Narrow zone containing pumice, wood, pitch, coral, and other debris marking edge of high storm waters in the back dune area of Padre Island, Texas.

straighter a storm moves on the same course, the higher the flood that is built up in its area of landfall.

On dune D1 the zone of flotsam rises from 8 ft above mean sea level at the southwest end of the dune to 10 or 11 feet above mean sea level on the east slope, at a point due west of the southwestern end of D2. The abundance of flotsam diminishes north of this point, the zone dropping to 2 ft above mean sea level. This distribution occurred seemingly because dune D2 shielded the northern end of dune D1 from southeast winds and strong wave action. At the western shore the debris rose highest along the axes of minor gullies, probably because wind waves and their swash were forced higher along the gullies. Between the minor gullies the flotsam zone was discontinuous.

The narrow zone of flotsam was also observed to be fairly widely and evenly distributed at 10 to 11 feet above sea level along the northeastern, southern, and southeastern slopes of dune D3.

The difference in regularity of flotsam deposition seems to show that the maximum heights were the result of wave run-up and that wave action was more uniform along the eastern flanks of D3 than it was along the western shore of the Rio Vista Lagoon on D1. Wave run-up, however, is not considered a possible agent of emplacement of the shells as they are uniformly distributed along an even slope at a low elevation and also are evenly bedded in clay. Waves do not break against such a surface on clay without causing gully erosion and steep bluffing. The present bluffs are many centuries younger than the shell deposits.

A few pieces of pumice were found by L. G. Huntley (personal communication) 20 ft above sealevel on the eastern summit of dune D3 at the top of a steep erosional bluff; however, as the eastern summit is a picnic area, it is likely that these pieces of pumice were not in place. The remote possibility that a few pieces of flotsam might have been tossed high up on a steep bluff by large waves breaking against it is to be considered.

Some of the bottles in the flotsam zone were partly filled with sediment. Some were irridescent from exposure to sunlight. Al-

though older looking than those on the mud flat, they had none of the deeply weathered opaque nature of the buried glass of the midden zones seen near Corpus Christi. The flotsam bottles were machine made and, therefore, were probably manufactured after World War I (Hunt, 1959). The hurricane after World War I that seems to have had the highest flood and the strongest waves here crossed the Gulf of Mexico from September 1 to 5, 1933, the center passing over the Rio Vista Lagoon. During this hurricane many sand dunes were washed away on the lower half of Padre Island and more than 40 washover channels were activated across Padre Island, some more than a mile wide (T. L. Bailey, in P. Reese, 1938 MS.). Water washing over Padre Island must have transported flotsam that had previously been deposited on this island into the Laguna Madre. A similar hurricane in 1916 (W. A. Price, 1956) deposited large driftwood logs 12 ft above mean sea level along the mainland shore of the northern Laguna Madre from Baffin Bay southward to the central mud flats, Kenedy County, but the water in the southern Laguna Madre was not raised appreciably (L. E. Rawalt, personal communication).

The flotsam zone on dunes D1 and D3 seems to be highest where high waves were driven directly against the south- and east-facing slopes. The manner in which the zone drops off to lower levels in areas protected from maximum wave height might falsely suggest a local domal up-warping if the hurricane origin of the flotsam were not recognized and if the flotsam were considered to be interbedded in the clay, rather than just a surface deposit, as it is.

SUMMARY AND CONCLUSIONS

A geological reconnaissance of interbedded shell layers in clay dunes rising from the flats of a small shallow lagoon near Port Isabel, Texas, revealed that the shells are principally submature, disarticulated, and fragmented valves of a small clam, *Mulinia lateralis*. This clam lives in large numbers in the adjacent, larger, coastal lagoon, Laguna Madre, and in bays along the Texas coast. Valves are dominantly oriented in the shell layers with the concave side down. It is concluded that these evenly bedded shells were incorporated in the dunes by wind. This conclusion is supported by experiments which indicate that moderate winds are capable of transporting shells up steep slopes. The apparently dwarfed nature of the shells in the beds might be the result of sorting by aqueous transport followed by wind sorting. If the clams lived in the small lagoon, they might have been prevented from reaching maturity because of periodic drying of the lagoon or because of their living under adverse environmental conditions. The low slopes and undisturbed nature of the shell strata would not agree with a hypothesis of wave run-up deposition which would require a beach, not a mud-flat environment.

Flotsam consisting of asphalt lumps, coral fragments, tropical beans, small lumps of wax or gum, pumice, scoria, slag or cinder, bottles, and lumber distributed on the slopes of dunes and elsewhere in the area at levels up to 11 ft above sea level are considered to have been deposited by hurricane waves, probably those of the hurricane of September, 1933—according to the known history of the area and the estimated age of manufacture of bottles in the flotsam.

ACKNOWLEDGMENTS

The authors wish to extend their appreciation to Mr. L. G. Huntly, who introduced the problem and kindly acted as guide and consultant in the field. Mr. Charles D. Wise assisted in wind experiments. The archaeological determinations cited were made or obtained by A. D. Krieger and T. N. Campbell of the University of Texas from Collections by W. S. Fitzpatrick, L. E. Rawalt, A. E. Anderson and W. Armstrong Price; the localities and positions were checked by Price.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 31, NO. 2, PP. 256–261
FIGS. 1–3, JUNE, 1961

SIZE DISTRIBUTION CHARACTERISTICS OF SHALLOW MARINE SANDS FROM THE CAPE OF GOOD HOPE, SOUTH AFRICA[1]

A. O. FULLER
University of Cape Town, South Africa

ABSTRACT

The results of detailed mechanical analyses of shallow marine sediments collected around the coasts of the Cape of Good Hope are presented. The sediments are quartz sands containing 20 to 40 percent shell fragments. Weight percentage cumulatives plotted on arithmetic-probability paper after phi-transformation show up to four modes. The cumulatives can in all cases be expressed in terms of log-normal components, and it has been found that the points of inflexion separating the three principal modes persistently occur at about 0.8 and 2 phi. The shapes of the cumulatives and positions of the inflexion points are not obviously related to shell content, analyses of acid leached sands giving the same results (with trivial exception) as their unleached counterparts. Consideration of the significance of the 0.8 and 2 phi inflexion points in terms of various factors which could induce polymodality, leads to the conclusion that the Stokes-Impact Formulae account for the 2 phi point and mixing of the suspension and traction loads is responsible for the 0.8 phi point.

INTRODUCTION

During the past two years a detailed investigation of the nature of bottom sediments, collected around the South African coasts, has been carried out as part of a program being conducted by the Department of Oceanography, University of Cape Town. Most of the samples come from the southwestern region, particularly from False Bay and from the coastal area between Saldanha Bay and Cape Town (fig. 1).

Samples have been collected from depths ranging up to several hundred fathoms, but the majority are of shallow marine sediments taken from depths of less than 10 fathoms. In all cases mineralogical and textural analyses were carried out. The shallow marine samples are all shelly sands containing from 20 to 40 percent acid soluble constituents. Alkali felspar is usually present in small amounts, and apart from occasional traces of glauconite and a minor heavy fraction, the remainder of the sands is quartz. Examination of projected grain profiles revealed a variety of degrees of roundness, subangular grains predominating.

It is the purpose of this paper to present the results of detailed mechanical analyses of these unconsolidated shallow marine shelly sands and to discuss the implications of persistent features recognized in their cumulatives.

[1] Manuscript received May 20, 1960.

COLLECTION AND TREATMENT OF SAMPLES

The samples were collected by diving to the bottom and plunging a cylindrical bottle into the sands. By twisting the bottle while maintaining a vertical pressure, a sample of approximately 300 gms, representing the upper 2 in of the bottom sediment, was taken. Throughout the procedure care was taken to disturb the sample as little as possible; that is, differential losses caused by artificial winnowing were avoided.

In the laboratory the samples were washed in fresh water and oven dried. A small sub-sample was split off for calcium carbonate determination, and mineralogical and shape analyses were carried out on the insoluble residues. A sub-sample of approximately 100 gms was selected for sieving. A complete set of B.S.S. sieves was used, the effective diameter of the screens having been determined by measurement under the microscope. Sieving was done dry by hand, agitation being continued until negligible amounts were passing the individual screens. This yields results of high accuracy, and reproducibility runs indicate that errors caused by hand sieving can be neglected.

The size data were phi-transformed and cumulated percentages plotted on arithmetic-probability paper.

GENERAL FEATURES OF THE CUMULATIVES

The typical appearance of the cumulatives of these shallow marine sands is shown in figure 2. It is evident that none is entirely log-normal although as a rule the major mode occupies 80 percent or more of the distribution and is clearly log-normal. With minor exception all the sands are either bi- or tri-modal.

An interesting feature of the cumulatives is that the break in slope between the major and secondary modes occurs very close to either 0.8 or 2 phi. At which of these two points it occurs depends on the average grain size of the sand. Samples whose cumulatives bracket the 0.8–2 phi range show changes in slope at both positions. The mode finer than 2 phi is not easily recognized unless it represents a substantial proportion of the sample.

It should be stated here that the features described above are not obviously connected with the fact that the samples examined are a mixture of two distinct grain populations, that is, a dominant quartz component and a comminuted shell fraction. The points of inflexion on the cumulatives do not appear to be related to the percentage carbonate, and mechanical analyses of leached samples (that is, carbonate free) show, with minor exception to be discussed later, no significant change in the shape or position of the cumulatives. This latter observation does not rule out the possibility that there is an interaction between the two populations, although the apparent independence of the inflexion points to the shell content noted above suggests that this is unlikely. Apparently the shell fragments and quartz grains in the size ranges represented in these samples behave in much the same way in a shallow marine setting.

COMPUTATION OF LOG-NORMAL COMPONENTS

The frequency of occurrence of log-normal distributions among particulate substances makes it desirable to attempt an analysis of polymodal cumulatives in terms of possible log-normal components. This has been done by the method of differences by Tanner (1959), but the method used by Harding (1949) was applied to the samples presented here. This consists essentially of fitting log-normal curves to the non-overlapping re-

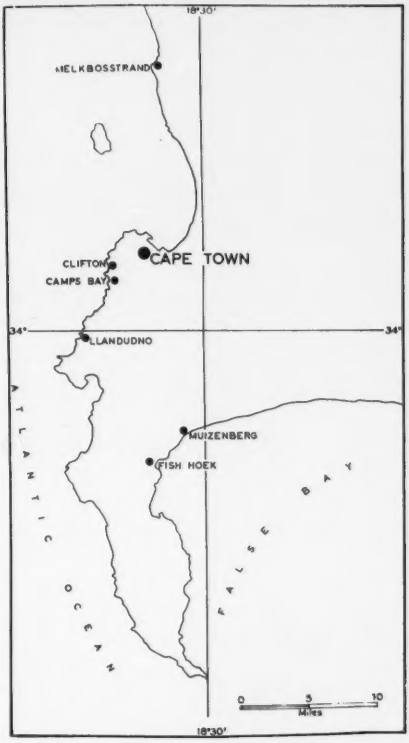

FIG. 1.—Location of coastal areas sampled.

gions of the cumulatives and requires simply that the points of inflexion on the curves be recognized in order that the correct proportions can be allocated to the various components of the distribution.

It has been possible to break down all the the cumulatives of the shallow marine sands studied into two or three log-normal components, depending on the number of modes present. Two examples are given (fig. 3). The followlng points may be noted

1.—The tri-modal example (fig. 3, no. I) has points of inflexion at about 0.8 and 2 phi. Other analyses of similar sands from different localities show inflexion points at approximately the same positions as in these examples. It is interesting to note that as the cumulatives shift laterally with overall change in grain size, the inflexion points

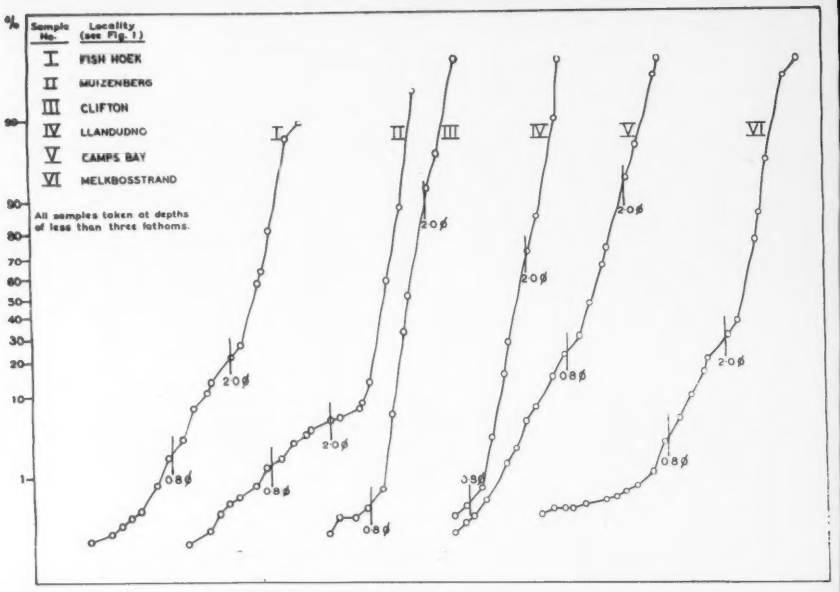

FIG. 2.—Characteristic weight percentage cumulatives of shallow marine shelly quartz sands from the Cape of Good Hope. The horizontal scale is indicated in each case by the position of the 0.8 and 2.0 phi points.

move vertically, maintaining an approximately constant position on the phi scale.

2.—In figure 3, no. I, the coarse tail of the cumulative, representing 0.2 percent of the sand, is not fitted by the curve drawn by addition of the three log-normal components. It occupies a special position in the distribution because it is the only segment affected by acid leaching. The cumulatives presented (fig. 3) might just as well have been drawn from leached sands, for, as stated above, the shell fraction does not appear to influence the shape of the curves, except for this small coarse tail, which disappears on leaching. It is evident that in shelly sands coarser than about 1.5 mm (as defined by sieving), the shell fragments begin to diverge from quartz grains in their response to distributing currents, so that a large shell fragment becomes hydraulically equivalent to a somewhat smaller quartz grain. This is probably a shape factor and becomes evident when the maximum and intermediate diameters of the shell fragments are much larger than their thicknesses (minimum diameters). It is probable also that the effective diameter of the square sieve mesh changes from that corresponding to the side of the square to the diagonal when the grain shapes become platy. Both these factors are considered to account for the pure shell component appearing at the coarse extreme of the cumulative (fig. 3, no. I).

3.—The degree to which a particular sand approaches unimodal log-normality depends upon the size range bracketed by the cumulative and the position of the median. None of the shallow marine sands studied by the author is wholly coarser than 0.8 phi or finer than 2 phi, so that, since the distributions straddle one or both of these grades, the cumulatives invariably are either bi- or tri-modal. However, it has been found that well sorted samples whose medians lie between these two sizes possess a major log-normal mode representing close to 99 percent of the sample.

DISCUSSION

The remarkable similarity in the shapes of the cumulatives of the shallow marine sands studied requires explanation. The main feature to be examined is the persistent occurrence of changes in slope of the curves at positions approximating 0.8 and 2 phi. It should be stated here that it is not the purpose of this paper to attempt to locate these inflexion points precisely or to attach standard errors to their positions as indicated by the data at hand. It is intended simply to draw attention to them as being characteristic features of these marine sands and to discuss possible inferences concerning their origin. Further, it has not been considered necessary to recalculate the data so as to convert the weight frequencies to number frequencies and hence to arrive at corrected mean particle diameters. The shift towards larger phi values which would occur if this correction were made, being proportional to the standard deviation of the distribution, is small for these well sorted sands and has been neglected in the discussion which follows.

Several possible interpretations of the features noted are

1.—Systematic sieve error: Considerable effort was made to determine the effective diameter of the sieves used in the study. Despite the high quality of the sieves employed, measurements made under the microscope over the entire area of the screens usually showed up variation in the mesh diameters. These were not of sufficient magnitude substantially to affect the precision of the work and each sieve was calibrated without too much difficulty. The possibility that gross errors in sieve sizes might account for the changes in slope observed is ruled out by the absence of these features in sands of similar size examined by the author and taken from nonmarine environments.

2.—Layering: There is a possibility that the bottom sediments sampled are stratified according to grain size and that two or more

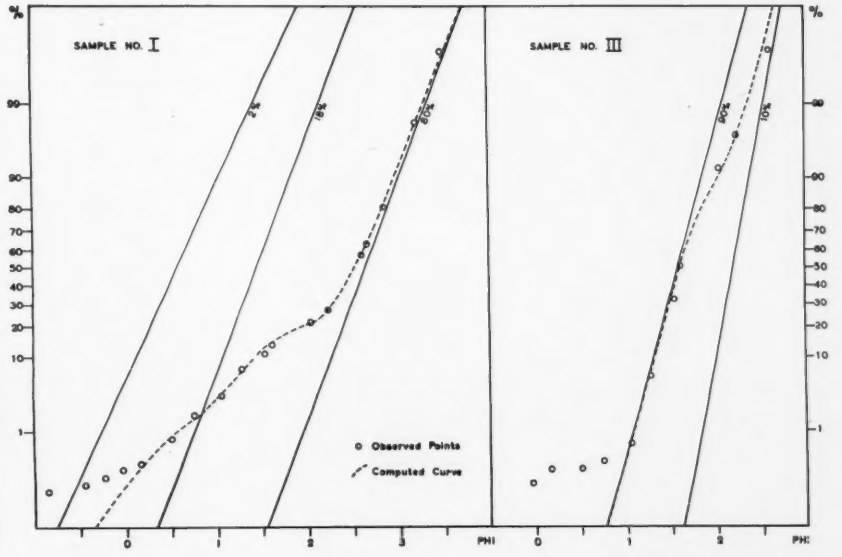

FIG. 3.—Log-normal components of cumulatives from samples nos. I and III (fig. 2.). The abscisa has been expanded to bring out changes in slope. Separate components have not been computed for the coarse tails which represent less than 1 percent of the distributions.

layers were mixed during selection. Several lines of evidence are against this interpretation. They are:

a.—Samples from widely separated localities show precisely the same distribution features.

b.—Repeated sampling of a single locality over a period of 8 months revealed no significant change in the characteristics of the bottom sands. The depths to which the corer was plunged into the sand on these occasions was not carefully controlled and it is difficult to imagine how the same proportion of various layers could have been selected on these occasions as would be required by the closely similar nature of the cumulatives found in each case.

c.—The fact that the points of inflexion occur at similar phi values in all the samples studied requires that, if layering is to be held responsible for the polymodality of the curves, the grain diameters represented in the layers be restricted, over wide areas, to two or three distinct modal sizes. It seems unlikely that this could be the case.

The arguments above do not altogether rule out the possibility that small scale stratification plays a part in accounting for the phenomena discussed, but the weight of evidence is against it.

3.—Mixing of traction and suspension loads: The recognition of these two fractions in all sediments transported by moving water makes it clear that the bottom samples examined here must consist of at least two modes related to these two forms of transport. Since many of the sands studied are tri-modal, the mixing of traction and suspension fractions cannot be the whole story. But it seems very probable that the 0.8 phi inflexion point separates the bottom and suspension fractions. This point will be mentioned again in a later section after the 2 phi inflexion has been discussed.

4.—Influence of Stokes' and Impact Settling Laws: Rubey (1933) has summarized information concerning the uniform settling velocities of particles in fluid media. He shows that Stokes' Law, in which the settling velocity is proportional to the square of the radius of the particle, theoretically does not apply to quartz spheres greater than 0.14 mm in water at 16° C. Above this size viscosity plays a less important role and settling velocity is more closely determined by the area of impact of the moving mass of water on the grain. The Impact Formula, applicable to these coarser sizes, derived by Rubey (p. 327) expresses uniform settling velocity as being proportional to the square root of the radius.

Experimental data for the settling of galena and quartz grains are graphically presented by Rubey (1933, p. 334–335). They show that for quartz grains at 16° C the Impact of Water Formula (Impact Law) and the Viscous Resistance Formula (Stokes' Law) merge in the vicinity of $\frac{1}{4}$ mm (2 phi), and that in the region of this size the settling velocities are expressed by a general formula derived from the above laws.

The remarkable persistence of an inflexion point at about 2 phi in the cumulatives of the shallow marine sands studied, and the coincidence of this size with the junction of the Stokes' and Impact Formulae makes it highly probable that the two phenomena are related and that the inflexion point separates modes whose behavior has been determined by these two laws.

CONCLUSIONS

The materials studied lie entirely within the size range 0.06–4.0 mm and dominantly within the range 0.09–1.5 mm. They are shelly quartz sands containing an average 20 to 40 percent shell fragments. Weight percentage cumulatives of phi-transformed data plotted on arithmetic-probability paper clearly indicate the presence of up to four modes connected by points of inflexion, two of which persistently occur in the vicinity of 0.8 and 2 phi. A third links a volumetrically insignificant coarse mode, made up entirely of platy shell fragments, with the remainder of the distribution.

It has not been possible from the data at hand to fix the positions of the 0.8 and 2 phi points of inflexion more precisely than about ± 0.1 phi. Nor is it established that these points are invariable and they are unlikely to be. They are, however, remarkably constant in the suite of samples studied.

The interpretation that their positions are determined by a traction-suspension load size boundary (0.8 phi) and the Impact-Stokes' Formulae junction (2 phi) requires that both points should shift in accordance

with the physical state of their environment. Thus, the 2 phi point should be temperature sensitive, and there are indications from work currently being conducted that this is the case. The position of the 0.8 phi point should depend on current velocities and should move in sympathy with the median as the sample becomes generally finer or coarser grained.

It was one of the purposes of this study to ascertain to what extent the shell component influences the shapes of the cumulatives. As has been pointed out there appears to be no correlation between shell content and cumulative characteristics within the sand range, and leached sands possess the same size distribution characteristics as their unleached equivalents. It would be necessary to investigate shell-free bottom samples from similar environments to determine whether or not there is any interaction between the shell and quartz grain populations.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 31, NO. 2, PP. 262–274
FIGS. 1–13, JUNE, 1961

DISTORTED OOLITES AND PSEUDOOLITES[1]

ALBERT V. CAROZZI
University of Illinois, Urbana, Illinois

ABSTRACT

Distorted oolites and pseudoolites are relatively rare occurrences in the geological column. They have been described in oolitic iron ores, phosphorites, limestones, argillaceous, and sideritic deposits. The shapes created by the distortion processes are very characteristic and independent from the mineralogical composition. They illustrate a complete gradation from plastic deformation to the rupture of rigid bodies. The distortion, which is localized in pockets or affects only isolated individuals, has always preceded the deposition of the cement and compaction wherever the latter has been active. The conclusion is reached that the distortion was generated during sedimentation in agitated conditions and resulted from the reciprocal impacts among oolites or pseudoolites at different stages of diagenetic induration.

INTRODUCTION

In this paper an oolite is defined as a spherical or subspherical body, 0.25 to 2 mm in diameter, of any composition usually displaying a nucleus around which at least one concentric layer has been deposited by an accretion process (Carozzi, 1960). The term pseudoolite is applied to a spherical body devoid of internal texture, which, however, may very often form the nucleus of associated oolites.

Distorted oolites and pseudoolites are apparently rare occurrences in the geological column. They display very characteristic features, independent of their mineralogical composition, which point to a single and general sedimentary mechanism. We have excluded from our discussion the normal oolites and pseudoolites flattened and deformed by the effects of mutual contacts during early compaction and those which have penetrated each other as a result of intergranular solution during late compaction.

REVIEW OF THE LITERATURE

Brief mentions and illustrations of distorted oolites and pseudoolites appear scattered in the geological literature, particularly in papers dealing with oolitic iron ores, but rarely are they accompanied by discussions or interpretations. Hence, to avoid repetition the review is limited to the most significant contributions.

The first mention of distorted oolites can be attributed to Gümbel (1885, p. 80, 173–174). He mentions that in the lower oolitic beds of the Wellenkalk many oolites are quite different from their typical spherical shape. They appear distorted into cylindrical or sausage-like bodies, irregularly bent, penetrated laterally by embayments, and often influenced by the shape of the neighboring individuals. Gümbel also describes similar features in pseudoolites frequently found in Jurassic limestones and proposes for them the name of half-oolite (Halboolithe). In spite of the lack of illustration, there is no doubt that Gümbel's description deals with the problem we are discussing here as pointed out by Frantzen in 1887.

The first complete description of distorted pseudoolites was given by Bornemann (1886, p. 277–278, plate VII, fig. 1) for a bed of pseudoolitic limestone called Bank η of the Lower Muschelkalk at Kirchthal, near Eichrodt in Thuringia. The pseudoolites (fig. 1 of this paper) appear as more or less well rounded bodies of dark cryptocrystalline calcite set in a cement of well crystallized calcite together with grains of granular calcite, fragments of crinoids, and pelecypod shells. In his picture, one can see very clearly zones, generally parallel to the bedding, in which the dark pseudoolites are strongly deformed, displaying notches and narrow apophyses joining adjacent individuals. The distorted bodies appear hooked together into zig-zag patterns and in groups recalling the typographical symbol of §, both trend-

[1] Manuscript received May 25, 1960.

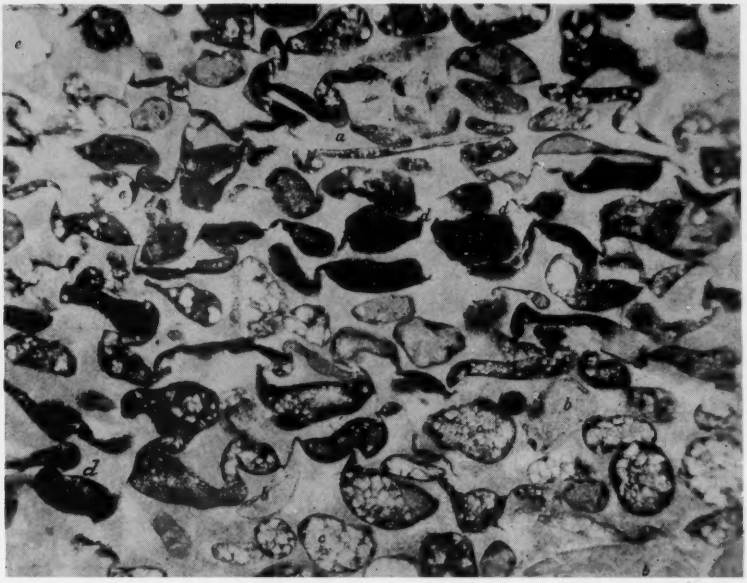

FIG. 1.—Pseudoolitic limestone, bed η, Lower Muschelkalk of Kirchthal, near Eichrodt. a: fragments of pelecypod tests; b: fragments of crinoids; c: pseudoolites of granular limestone; d: distorted pseudoolites; e: voids due to weathering. ×23, parallel nicols. This is Bornemann's 1885 (1886), figure 1 of plate VII.

ing parallel to the bedding.

Bornemann calls the distorted pseudoolites "corroded limestone grains" because he interprets them as the result of a corrosion in place before deposition of the cement and caused by the alteration of pyrite. He describes his figure as follows: "the thin section shows a superposition of zones of perfect preservation and of others in which alteration has been active. In the former (lower portion of the picture), the limestone grains display an appreciable encrustation of pyrite which appears also as a fine powder along the crystal boundaries. In the zones of alteration, the pyrite was decomposed into iron sulfate which corroded the dark cryptocrystalline grains and stained them in brown. In the presence of abundant pyrite, the sulfuric acid developed was sufficient to change an appreciable portion of the limestone into gypsum. The latter has left after dissolution cavities filled with iron hydroxide."

A year later Frantzen (1887, p. 90–92, plate III, fig. 2 to 4) described the first distorted oolites in the bed of oolitic limestone called Bank β of the Lower Muschelkalk of Heldrastein in Thuringia. He discusses his observations in the following terms: "in figure 2 of plate III, (fig. 2 of this paper) there are normal oolites on the left side whereas on the right they have been modified by the movement of the water. The oolites have been distorted, squashed and sometimes broken into two parts along a sharp rupture line. Some individuals display their broken fragments still side by side. The same types of deformations are shown by oolites made of dark cryptocrystalline calcite or of clear calcite. Figure 3 (fig. 3 of this paper) of the same plate shows another portion of the same slide with oolites squashed by the pressure of the water. Figure 4 (fig. 4 of this paper) shows a case in which distortion has been carried so far that the elongated bodies could not be identified as

FIG. 2.—Distorted oolites, oolitic limestone β, Lower Muschelkalk of Heldrastein. ×58, parallel nicols. This is Frantzen's (1887) figure 2 of plate III.

oolites if all transitional terms were not present in the same deposit."

Frantzen adds that Bornemann's picture may be interpreted as showing that the pseudoolites were also soft during their formation and even softer than the oolites of Heldrastein, some of which display fragments with sharp boundaries. He reaches the conclusion that the normal oolites indicate relatively quiet water and the distorted ones a very agitated environment, proposing the name of empodoolites (Empodoolithe) for the latter. Frantzen's pictures 2 and 3 show oolites oriented at random in a cement of well-crystallized calcite in which a segment of the concentric envelope has been rotated along a hinge-line or displaced inside the individuals for a variable distance. These movements have often been accompanied by a wrinkling of the displaced segment and may end in a complete shearing or shattering of the oolites. A more elaborate discussion of these forms will be given later in this paper. Frantzen's figure 4 (fig. 4 of this paper) displays a situation in which the distorted oolites are not oriented at random but have been further flattened and appreciably oriented parallel to the bedding. The cement is well-crystallized calcite as in the other cases, but is less abundant. As a result, the distorted oolites come in contact with each other much more frequently and have reciprocally affected their shapes. This indicates a localized compaction of the distorted individuals before the introduction of the cement.

In the first volume of his monograph on the oolitic iron ores of France, L. Cayeux (1909, p. 18–34) mentions but does not illustrate distortion phenomena. These occur in oolites of red hematite in a cement of siderite in the Silurian ore of May-sur-Orne (Calvados) and are described as follows: "the deformation is preferably concentrated along certain zones of the ore where the oolites are almost molded on each other

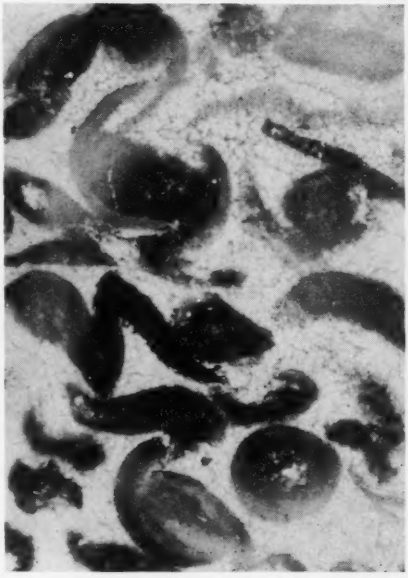

FIG. 3.—Distorted oolites, oolitic limestone β, Lower Muschelkalk of Heldrastein. ×60, parallel nicols. This is Frantzen's (1887) figure 3 of plate III.

without any intercalation of cement. In some cases, the oolites may be distorted to such an extent that their original oolitic nature has almost vanished. The deformation also exists, but less pronounced, among isolated individuals."

In his second volume dealing with the Mesozoic oolitic iron ores, Cayeux describes (1922, p. 169–171, plate XI, fig. 24) a chloritic iron ore of the Upper Liassic of Lorraine in which distorted chloritic oolites appear strongly flattened parallel to the bedding in a very reduced amount of chloritic cement. Here again the distortion, even where realized with its maximum intensity, is strictly limited to a portion of the bed and does not develop through its entire thickness. Cayeux concludes: "It is probable that the causes of the phenomenon must be looked for in the deposit itself. Possibly it could be attributed to changes in the physical state of the oolites. The process might then be compared to the folds created by the change of anhydrite to gypsum." In the two cases just discussed, we have conditions similar to those already described by Frantzen where distorted oolites have been further flattened by local compaction before introduction of the cement.

A general discussion of distortion among oolitic iron ores was announced by Cayeux for the third volume of his monograph; unfortunately it was never published. However, in 1935, in his monumental monograph on carbonate rocks, Cayeux gives a detailed description and discussion of two unusual examples of distorted oolites in specimens from the Jurassic of an unknown locality from the margins of the Massif Central (fig. 5) and from the Muschelkalk of Azerailles, Meurthe-et-Moselle (fig. 6). The two specimens (p. 233–235, plate XV, fig. 55 and 56) display the same types of distortion which he attributes to contraction and stretching, pointing out the following features: "The specimens show stretched oolites, notched oolites, and oolites stretched and notched at the same time. The starting point of the deformations is a limestone in which the oolites appear more or less largely separated from each other and not contiguous. The following situations may be observed in order of increasing complexity (fig. 5 and 6):

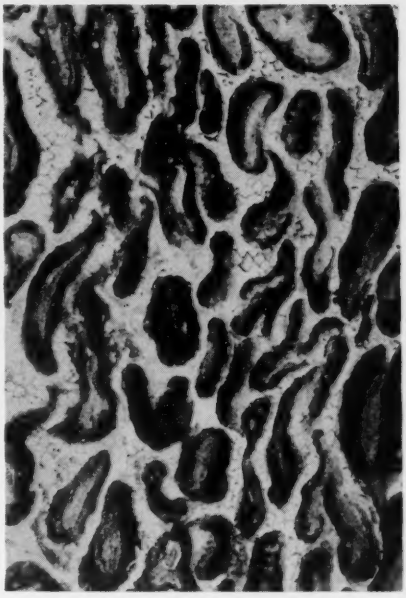

FIG. 4.—Distorted and compacted oolites, oolitic limestone β, Lower Muschelkalk of Heldrastein. Camera lucida drawing, ×60, parallel nicols. This is Frantzen's (1887) figure 4 of plate III.

1. Two adjacent oolites are joined to each other through the extension of one of them.
2. Two oolites are joined to each other by means of an arcuate apophysis, very thin in its middle portion and sometimes broken by excess of stretching.
3. In most of the preceding cases, the junction of adjacent oolites takes place at the points where they come the closest or almost. There is a quite different situation where the little apophysis joins the opposed ends of two adjacent oolites.
4. Oolites appear notched to a variable extent by wedge-like cracks which, where carried to exaggeration, lead to an almost complete disruption of the bodies.
5. In a general manner, where oolites are notched in such a fashion, the feature is repeated on many neighboring individ-

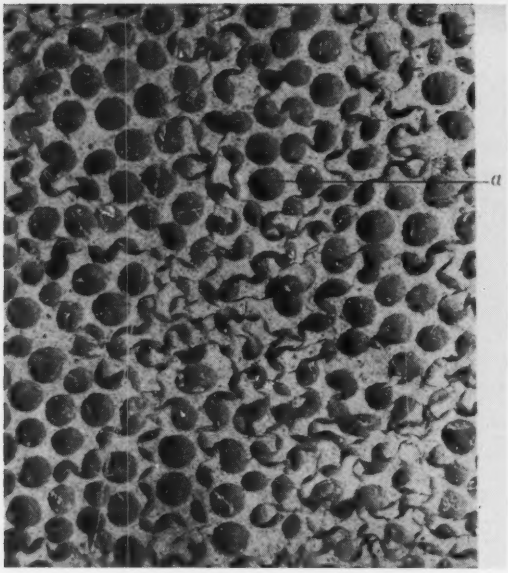

FIG. 5.—Distorted oolites from an oolitic limestone, unknown locality along the margin of the Massif Central, France. Polished surface, ×4. a: oolite apparently not distorted. This is Cayeux's (1935), figure 55 of plate XV (permission of Masson et Cie, Paris).

> uals. At the same time, the lips of the notches appear to continue into arcuate apophyses, forming elegant curves joining similar features of neighboring oolites. For instance, two individuals, very widely separated by a distance which is sometimes greater than their longest axis, may be joined through the cement by narrow apophyses which always keep a perfect individuality. In the cases of maximum complication, oolites showing the deformations described above may build up corkscrewed series (fig. 5, 6). It is important to point out that such a complex deformation is not present all over the entire specimen but is concentrated in given areas which, however, contain scattered oolites which have kept their original shape."

Cayeux feels that one single explanation should be applied to the distortions in oolitic iron ores and in limestones and presents the following discussion: "the junctions between the oolites, their size, shape and the fragility of the arcuate apophyses require a formation in place without any mechanical actions foreign to the deposit itself. It looks as if oolites, originally in mutual contact and in very plastic condition, had been submitted to an important reduction of volume in a cement which would oppose only a very weak resistance to the movement of materials. The oolites pulled in different directions by the effect of the numerous original points of mutual contact would remain attached by the development of apophyses. The size and shape of the latter are a function of the magnitude of the contraction; their number and position a function of the contact points. Consequently, the apophyses result from the different tractions to which the oolites have been submitted. In this interpretation, the oolites themselves are at the origin of their distortion but nevertheless, the mechanism remains highly enigmatic. If the proposed explanation were true, the cementation processes of such rocks would be extraordinarily complex and

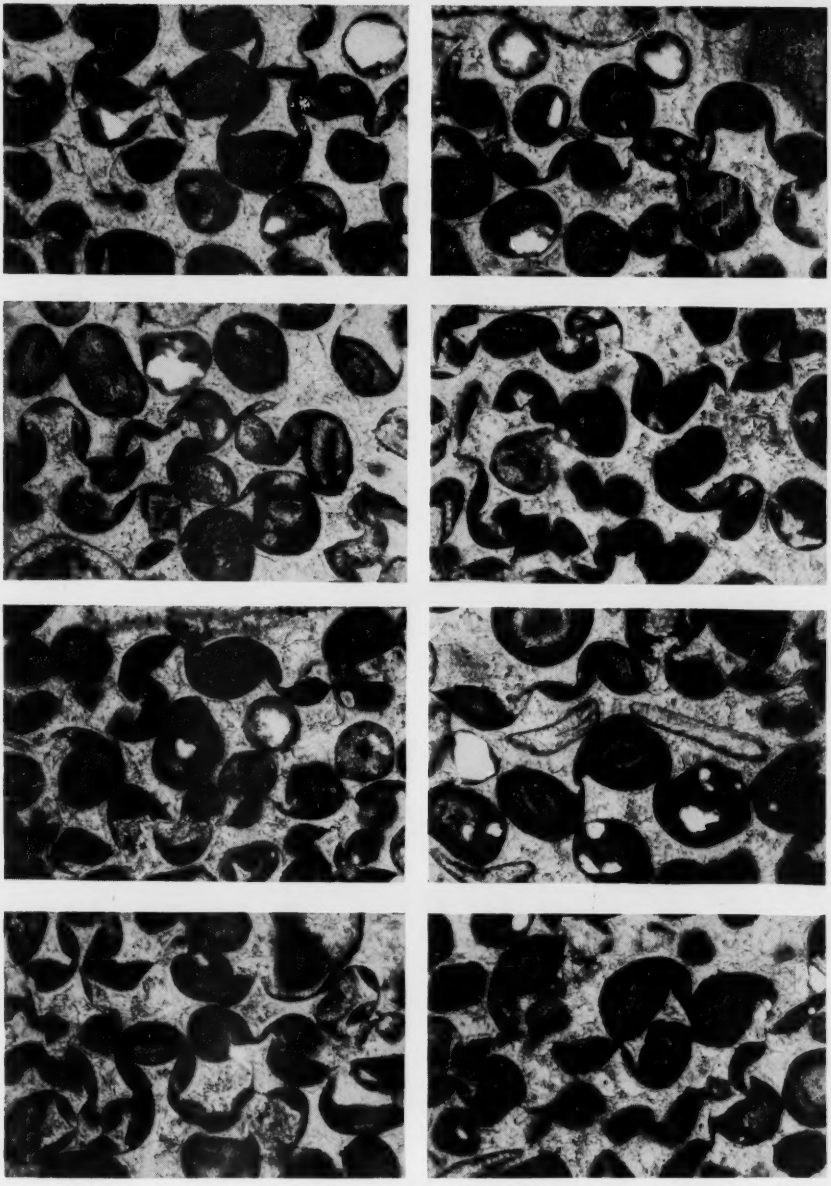

FIG. 6.—Distorted oolites from an oolitic limestone of the Muschelkalk of Azerailles (Meurthe-et-Moselle), France, ×25, parallel nicols. White areas are holes in the thin section.

would imply changes of volume of a magnitude unsuspected up to now in calcareous environment."

Cayeux rejects the interpretations proposed for similar deposits by Bornemann and Frantzen as inadequate to explain the observed facts.

Lucas (1942, p. 308, fig. 127) in his description of the mountains of Ghar Rouban and of Sidi El Abed, Algeria, mentions oolites distorted by notching and stretching similar to those discussed by Cayeux. These oolites occur at the base of the Kimeridgian-Portlandian (J 5) of the Bled Tirheza. No additional information is given concerning their characters or genesis.

Van Tassel describing siderite beds with argillaceous oolites and pseudoolites in the Westphalian of Belgium, illustrated and briefly mentioned some cases of distortion (1955, p. 366–367, plate A., fig. 3 to 5):

Figure 3 of plate A (fig. 7 of this paper) shows oolites of kaolinite with well-developed concentric texture built by layers of

FIG. 7.—Distorted oolites of impure kaolinite in a pyritic cement (black), Westphalian, Charbonnage du Poirier, Charleroi, Belgium. The oolites have a core of carbonaceous material; their original concentric texture appears partially destroyed by developments of pure microcrystalline kaolinite. ×50, parallel nicols. This is Van Tassel's (1955) figure 3 of plate A.

FIG. 8.—Distorted pseudoolites of kaolinite hooked together in a cement of microgranular siderite. Scattered rodlets of apatite. Westphalian Charbonnage du Poirier, Charleroi, Belgium. ×50, parallel nicols. This is Van Tassel's (1955) figure 5 of plate A.

different color around a relatively small core of carbonaceous matter. The oolite on the extreme right side of the picture reveals that a segment of its rather thin concentric envelope has been sharply bent at its upper end like a hair-pin and terminates at the lower end by a sharp rupture line. The flap thus created shows, in comparison with the remaining portion of the concentric envelope, a decreased curvature, appearing almost flat. The flap has evidently been rotated inside the oolite at the expense of the relatively large core of carbonaceous matter, an appreciable portion of which has been eliminated. This process of distortion will be analyzed with more details in the next section.

Figure 5 of plate A (fig. 8 of this paper) shows well-developed pseudoolites of fine-grained kaolinite devoid of internal texture and of core. In the middle of the picture extends a row of three distorted individuals hooked together by their apophyses.

Edwards, in his description of oolitic iron formations in Northern Australia (1958, published 1959, p. 668–682, fig. 4, 13 and

14), has given some of the best illustrations ever published of distorted oolites but did not elaborate at length on their possible origin. He mentions, however, that the same type of cement encloses distorted and spherical oolites, indicating that cementation occurred after the deformation of the oolites.

His figure 4 (fig. 9 of this paper) shows an oolitic ironstone from Roper Bar, Northern Territory, of late Proterozoic age, in which hematite oolites are set in a micro-crystalline cement of quartz. In the lower half of the picture appear from left to right, three distorted individuals. The first one has been split open into two parts which have rotated outward limiting a sharply defined V-shaped crack. The oolite in the middle shows a deep notch made by a flap which apparently was pushed obliquely inside the body and curled on itself. The third oolite displays a flap flattened in the same manner as illustrated by figure 3 of Van Tassel (1955). All these distorted individuals are set in the quartz cement and display only very limited contacts with neighboring normal individuals.

Figures 13 and 14 display in a remarkable way distorted oolites of chamosite in a cement of crystalline siderite from Upper Proterozoic deposits in the Constance Range area, Northwestern Queensland. The distorted oolites are associated with normal ones indicating once more that cementation occurred after the processes of distortion. It is appropriate to take advantage of these excellent conditions of preservation to describe here two very characteristic sections of distorted oolites which occur in all previously discussed cases. The first one is shown by the oolites in the middle and right middle of figure 14 (fig. 11 of this paper). In both individuals a segment of the concentric envelope, extending from one of the summits of the elliptical section to approximately $\frac{3}{4}$ of its longest axis, appears sharply bent at one end like a hair-pin and terminates at the other by a straight or curved rupture line. The flap thus created displays, in comparison with the remaining portion of the envelope, a decreased curvature or even has been completely flattened. It has been rotated around its hinge inside the original outline of the oolite and for a variable distance. The penetration of the flap inside the oolite requires a plastic deformation of the latter for obvious geometrical reasons, the external dimension of the flap being larger than the internal dimension of the opening. When such a plastic deformation was not enough, the penetration of the flap was partially hindered, and the latter may display a wrinkling on itself or a refolding of its end. The displacement of the flap reaches its maximum when it comes in contact with the concave internal margin of the opposite portion of the concentric envelope. Naturally, the penetration of the flap has always been made at the expense of the core which has suffered a great amount of reduction reaching often almost complete disappearance. As shown in the upper middle portion of figure 13 (fig. 10 of this paper), the hinge-line of the flap may appear partially broken in its internal layers which are separated from one another to a variable extent and also individually wrinkled.

The second typical section is shown by the oolite in the upper-central portion of figure 14 (fig. 11 of this paper). Here the concentric envelopes appear sharply ruptured at two

FIG. 9.—Distorted hematite oolites (black) in a cement of microcrystalline quartz. Oolitic ironstone, Upper Proterozoic from Roper Bar, Northern Territory, Australia. ×35, crossed nicols. This is Edward's 1958 (1959), figure 4.

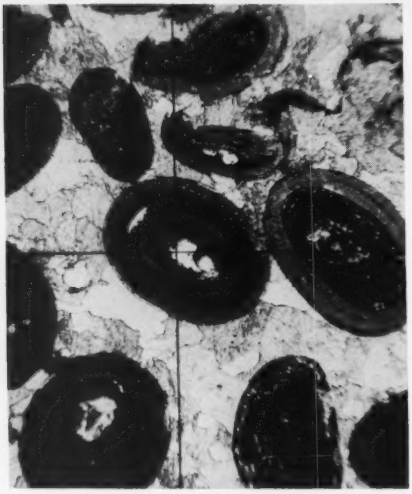

FIG. 10.—Oolitic siderite, Upper Proterozoic of Constance Range, Queensland, Australia showing normal and distorted oolites consisting of outer concentric rings of a chamosite-like substance enclosing darker shells containing black opaque carbon and siderite (white). The cement is crystalline siderite. ×30, parallel nicols. This is Edward's 1958 (1959) figure 13.

points, no hinge line is visible, and a flap also showing a decreased curvature appears displaced, but not rotated, inside the original outline of the oolite. Occasionally, concentric layers of the flap appear wrinkled and separated from each other. Here also it should be pointed out that the external size of the flap is larger than the inner dimension of the opening through which it moved. Hence, the displacement requires a plastic deformation of the oolite. The core has been strongly reduced to an elliptical and narrow slit. As will be seen later, these two sections occur in reality at right angle to each other and across one of the basic forms of distortion.

Laugier, describing salt-bearing beds in the Middle Liassic of Lorraine (1959), gives petrographic details on peculiar oolites consisting essentially of magnesite with some halite in the concentric rings and set in a cement of anhydrite. He illustrates a distorted oolite (plate III, fig. 6) and a corroded oolite (plate III, fig. 7) whose shape he attributes to replacements resulting from the growth of the anhydrite crystals of the cement. The aspect of this particular oolite is identical to that of many others described in this paper: it shows clean-cut boundaries, an undulated flap displaced toward its center, and no appreciable change in texture of the surrounding cement. These features seem in favor of a mechanical distortion rather than replacements, the latter being shown beautifully elsewhere in the same paper (plate IV. fig. 7, 10 to 12).

Zadnik has kindly communicated to the writer several thin sections of oolitic dolomites from the Upper Cambrian of the Middle Delaware Valley, near Easton, Pennsylvania, which display scattered zones of distorted oolites in all details similar to the cases discussed above.

ANALYSIS OF THE SHAPES OF DISTORTED OOLITES AND PSEUDOOLITES

From the review of published pictures and from thin section studies of samples from

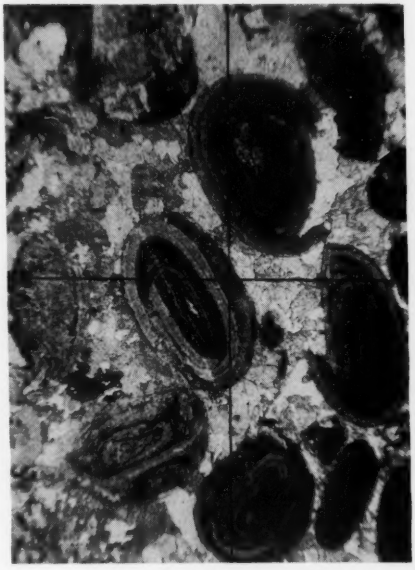

FIG. 11.—Distorted chamositic oolites adjacent to the band of rock shown in figure 10. ×30, parallel nicols. This is Edward's 1958 (1959) figure 14.

the Muschelkalk of Azerailles (Meurthe-et-Moselle), France, the Westphalian of the Charbonnage du Poirier, Charleroi, Belgium, and the Upper Cambrian of the Delaware Valley, it has been possible to assemble a great number of differently oriented sections of distorted oolites and pseudoolites. At a first glance, the variety of the shapes appeared quite large but soon the repetition of similar forms indicated three main groups of basic types to which all the observed shapes could be derived by increased stretching and distortion. Such a derivation was confirmed by constructing plastic models and cutting them along oriented sections.

Group 1

It includes the most common shapes resulting from the rupture of the outer shell of oolites and pseudoolites accompanied by an elimination of a variable proportion of the core. The reconstruction by models of such ruptured oolites shows that the two sections described in the deposits of the Constance Range area are located at right angles to each other. They cut across a spheroidal or ellipsoidal body in which a flattened flap corresponding to a small circle has been pushed inside by rotation along a short hinge-line (fig. 12 a, b).

According to the size of the flap and the thickness of the external skin which has been ruptured, apophyses are created which vary in shape from sharply acute types (increased by further stretching) to rather massive beak-like forms (fig. 13, 1 to 7). The flap may display a curling of its end (fig. 13, 3) or several wrinkles (fig. 13, 2). It may have its hinge-line broken (fig. 13, 4), and such a condition may lead to a complete shattering of the body (fig. 13, 6).

In the section at right angles to the preceding one (fig. 13, 8 to 13), the flap may also appear wrinkled (fig. 13, 11) and the two apophyses strongly stretched in many instances (fig. 13, 12 and 13). Oblique and tangential sections across distorted individuals belonging to the first group may give quite unusual shapes (fig. 13, 16 to 21). In some cases (fig. 13, 22 to 24), the flap no longer appears flattened but is curled on itself displaying an increased curvature in comparison with the rest of the oolite (fig. 12, c). In such a case, a rather thick beak-

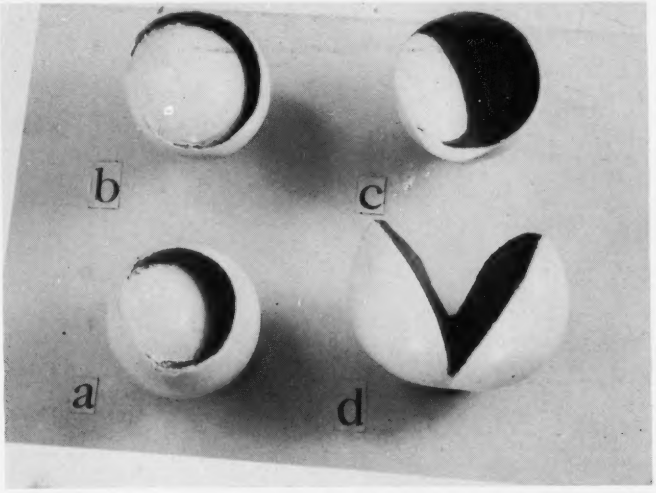

FIG. 12.—Schematic models of the major types of distorted oolites. a, b: shapes resulting from the penetration of a flattened flap (group 1), c: shape resulting from a curled flap (group 1), d: shape resulting from squashing and rupture along a great circle (group 2). See text for additional explanations.

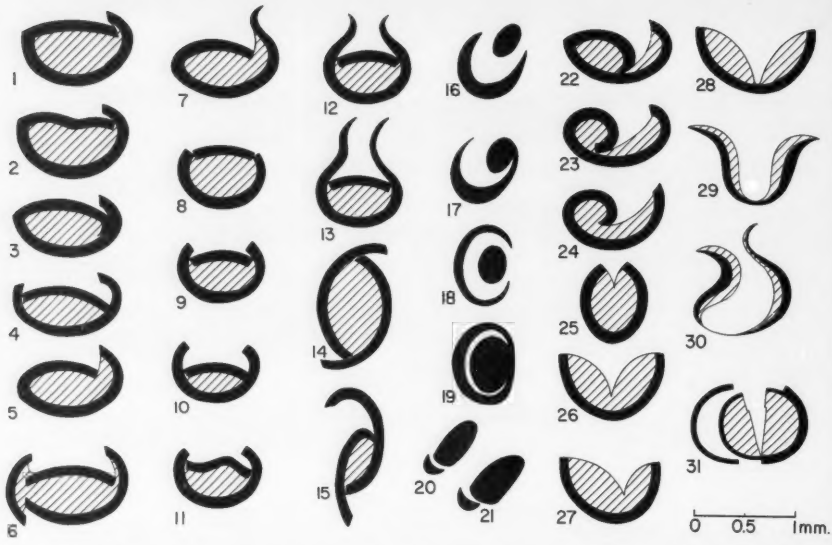

FIG. 13.—Schematic representation of the major types of distorted oolites as they appear in thin section. Shell of concentric rings: black; core: oblique ruling. 1–24: shapes of group 1; 25–30: shapes of group 2; 31: shapes of group 3. See text for additional explanations.

like apophysis is generated, particularly when the curling has taken place without the flap being rotated too much inside the oolite.

Group 2

In this group are included the shapes resulting from the plastic squashing of oolites and pseudoolites into two parts usually along a great circle (fig. 12, d). The individuals appear split open to a variable extent (fig. 13, 25 to 27). In advanced cases, the fragments are deformed and remain attached to each other only by their outer skin; wavy distortion and stretching are frequently noticed (fig. 13, 28 to 30). This type of distortion displays all gradations between cases in which a small loss of volume has occurred to cases in which the core has been largely eliminated, leaving only distorted and empty outer skins. These may either remain in loose connection or be completely detached or hooked together.

Group 3

This group generally includes oolites which have been broken along well-defined lines but not distorted. The rupture appears in most of the cases as a V-shaped crack cutting across concentric envelopes and the core, the two parts have commonly been rotated away from the crack (fig. 13, 31). In other cases, the oolites appear decorticated, showing indentations caused by fragments of their concentric rings torn off or in the process of being detached. The isolated portions of concentric rings resulting from this process may be found isolated in the cement (fig. 13, 31).

RELATIONS BETWEEN DISTORTED AND NORMAL OOLITES AND THEIR INTERPRETATION

A certain number of characteristic relations are present in all the deposits containing distorted oolites and pseudoolites no matter what their mineralogical composition may be. They are following:

1.—The distorted individuals are not uniformly distributed in the deposits but concentrated in irregular pockets and in zones parallel to the bedding.

2.—The distorted individuals may either be isolated and oriented at random or appear hooked together by their apophyses, in which case they are oriented parallel to the bedding, forming irregular chains. The individuals hooked together frequently display a stretching of their apophyses and advanced distortion of their general shape.

3.—In some instances, distorted individuals have been locally flattened by later compaction and molded on to one another.

4.—Normal oolites and pseudoolites are associated in the same beds with distorted ones, but both kinds appear rarely in contact with each other. It should be pointed out, however, that according to their orientation some sections across distorted individuals may simulate normal ones.

5.—There are no geometrical relations in the deposits indicating that the distorted individuals have been affected in their shape by the associated normal oolites and pseudoolites except in the cases of local compaction following distortion.

6.—The shapes described in the first group of distorted individuals imply a phase of rupture of the outer skin preceded and followed by a plastic deformation. The shapes of the second group result from an entirely plastic deformation and those of the third display an entirely rigid behavior of the bodies. The implication of these facts is the coexistence of individuals at different stages of a process of induration which develops from the periphery toward the inside of oolites and pseudoolites.

7.—The cement displays no effects of the deformation and no traces of the material building the cores of some oolites and which must have been eliminated by some of the types of distortion. The cement does not show any modification of texture or composition wherever it includes normal or distorted individuals as well as where distorted oolites have been further flattened by local compaction.

In order to explain satisfactorily all the relations just described, the mechanism of distortion must have been active only during the time interval corresponding to the deposition of certain zones of the beds displaying variable thickness and sometimes only in very localized spots. This is also shown by the fact that the agent which has broken, squashed, and strongly distorted certain oolites and pseudoolites has also hooked them together and stretched their apophyses, building complex chains or local concentrations.

The process of distortion was completed before the introduction of the cement. Hence, it is concluded that the agent of distortion can only be of subaqueous nature, corresponding to strong waves or currents sweeping the bottom, generating local eddies and creating reciprocal impacts among oolites and pseudoolites freshly deposited and at different stages of induration. These conditions stress once more the rapidity of diagenetic processes.

DISCUSSION OF EARLIER INTERPRETATIONS

Our conclusions are identical, in essence, with those expressed in 1887 by Frantzen who considered the agitation of the water as the agent responsible for the distortion.

The idea of corrosion in place after deposition presented by Bornemann (1885) cannot be sustained, mainly because of the identical shapes generated in oolites and pseudoolites of different mineralogical composition. Cayeux (1935) made basic contributions to the question by stressing the fact that the distortions were present in isolated individuals and in localized portions of the beds. He considered that the oolites themselves were at the origin of their distortion and that a single explanation should be applied to all cases, whichever their mineralogical composition happened to be. However, by assuming that the distortion took place after the deposition of the cement, Cayeux was forced to assume very complex and unusual properties for both the oolites and the cement. As a result, his tentative explanation contains contradictions and does not agree with the observed facts.

ACKNOWLEDGMENTS

This investigation has been made possible by the kind help of A. B. Edwards, F. Kraut, R. Van Tassel, and V. Zadnik who supplied the author with materials for thin-sections and illustrations from their own publications. This generous cooperation is gratefully acknowledged.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 31, NO. 2, PP. 275–287
FIGS. 1–7, JUNE, 1961

BRECCIA AND PENNSYLVANIAN CAVE FILLING IN MISSISSIPPIAN ST. LOUIS LIMESTONE, PUTNAM COUNTY, INDIANA[1]

NED M. SMITH, JACK A. SUNDERMAN, AND WILTON N. MELHORN
Indiana Geological Survey, Bloomington, Indiana and Purdue University, Lafayette, Indiana

ABSTRACT

A limestone breccia and several bodies of shale and sandstone in Mississippian St. Louis Limestone were discovered in a quarry opened during the summer of 1959 in the SE¼NW¼ sec. 15, T. 15 N., R. 4 W., Putnam County, Indiana. A small mass of sandy limestone conglomerate overlay part of the breccia. Nearly all these bodies have been removed in quarrying.

The breccia and the shale-sandstone masses appear to have originated from two separate geologic processes which occurred at two different times. The origin of the breccia is in doubt because not enough critical evidence is available to prove conclusively any single origin. The authors believe, however, that the breccia probably is the product of a submarine rock slump during St. Louis time which was triggered by the tectonic activity that initiated early movements along the Mt. Carmel Fault. Other possible origins, such as solution of evaporites accompanied by collapse of overlying rock or formation of caves in a karst terrain followed by roof collapse, are not supported by the evidence observed.

The shale-sandstone bodies are believed to be rocks of Pennsylvanian age which were deposited in caverns developed during the Mississippian-Pennsylvanian erosion interval. The limestone conglomerate probably is of the same age as the shale-sandstone bodies.

INTRODUCTION

Small masses of shale and sandstone and a body of limestone breccia (fig. 3) were exposed when the new Harris quarry in the middle Mississippian St. Louis Limestone was opened during the spring and summer of 1959. Subsequent quarrying has removed the breccia and many of the shale-sandstone bodies. This paper describes these deposits, relates them to the surrounding limestones, and discusses the evidence for their ages and manner of emplacement.

The Harris quarry is approximately 2 miles southwest of Bainbridge and approximately 7 miles north of Greencastle, Putnam County, Indiana, in the SE¼ NW¼ sec. 15, T. 15 N., R. 4 W. (fig. 1). The features described were present only in the west wall of the quarry (fig. 2).

GENERAL GEOLOGIC RELATIONSHIPS

About 5 to 10 feet of glacial till (figs. 3, 4) overlies bedrock at the quarry and is stripped away before quarrying. Intervening between the base of the till and relatively unaltered limestone is a zone containing limestone saprolite. The breccia was composed of fragments of limestone in a calcareous siltstone matrix. The east-west extent of the breccia was observed as the quarry expanded westward. Although the exact position of its eastern boundary is unknown, the breccia was at least 50 ft long in its east-west dimension (fig. 2). The breccia extended from the top of the quarry to an unknown depth below the quarry floor. Beds of conglomeratic material were present at the top of the westernmost exposure of the breccia. This conglomeratic material was not well enough exposed, however, to determine its precise relationship to the breccia and to the bedded St. Louis Limestone.

Before removal, a 15-ft wide mass of poorly cross-bedded shales and sandstones and a smaller body of similar materials were exposed about 14 ft south of the breccia (figs. 2, 3). The large shale-sandstone mass extended from the top of the rock to the floor of the quarry 17 ft below; its total downward extent is unknown. The 3-ft wide smaller body, about 7 ft south of the larger mass, was partly capped by St. Louis Limestone and did not reach the quarry floor (fig. 3). A third shale-sandstone mass was found about 30 ft north of the breccia (fig.

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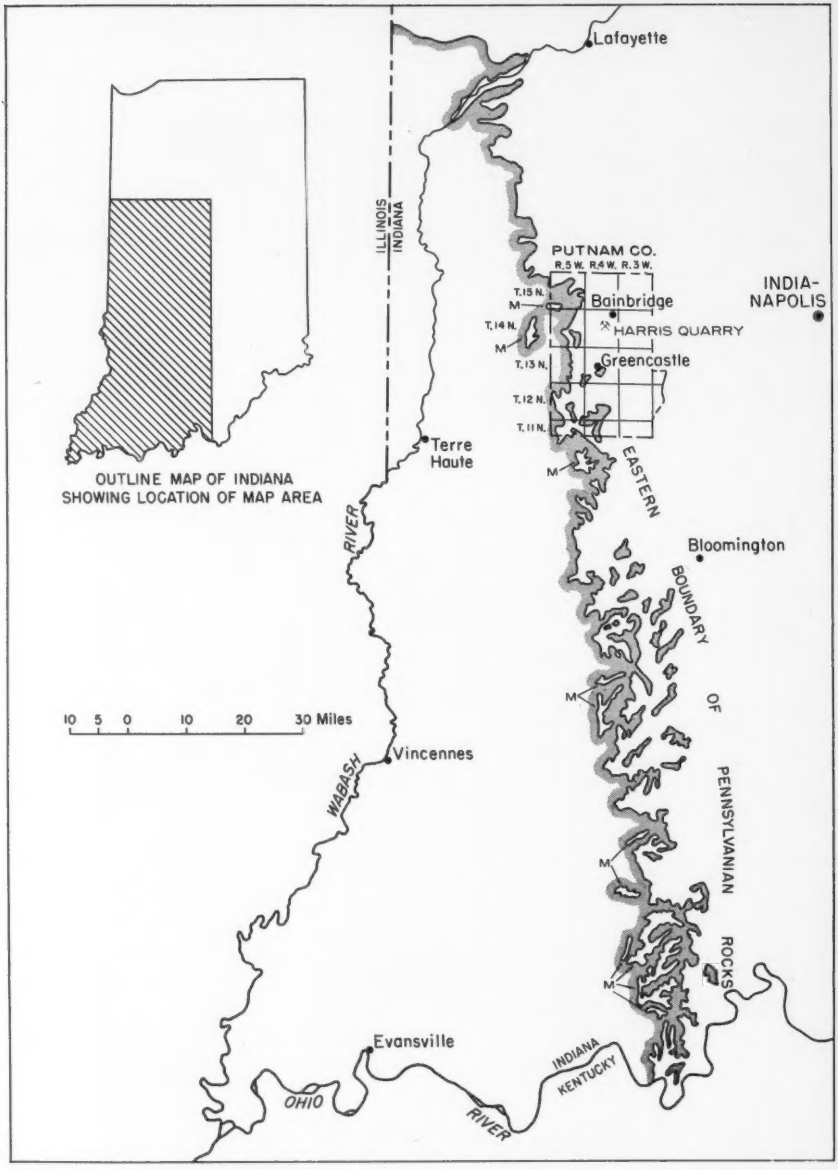

FIG. 1.—Map of southwestern Indiana showing the eastern boundary of Pennsylvanian rocks (stippled), the principal Mississippian inliers (M), principal Pennsylvanian outliers (stippled), and the location of the Harris quarry.

2). This third mass was about 5 ft wide and was overlain by about 4 ft of St. Louis Limestone. It was covered at its base by broken quarry rock. A fourth mass of shale about 1 ft in diameter was uncovered near the northwest corner of the quarry, about 100 ft north of the third shale-sandstone body (fig. 2). This small mass was about 15 ft above the quarry floor and was capped by about 2 ft of normally bedded St. Louis Limestone.

The St. Louis Limestone beds of this area dip southwestward approximately ½° (30 ft per mile), but in the Harris quarry these beds are undulatory and dip as much as 30° locally. The bedded limestone immediately south of the breccia dipped north into the breccia at about 7° (fig. 4). The breccia lay

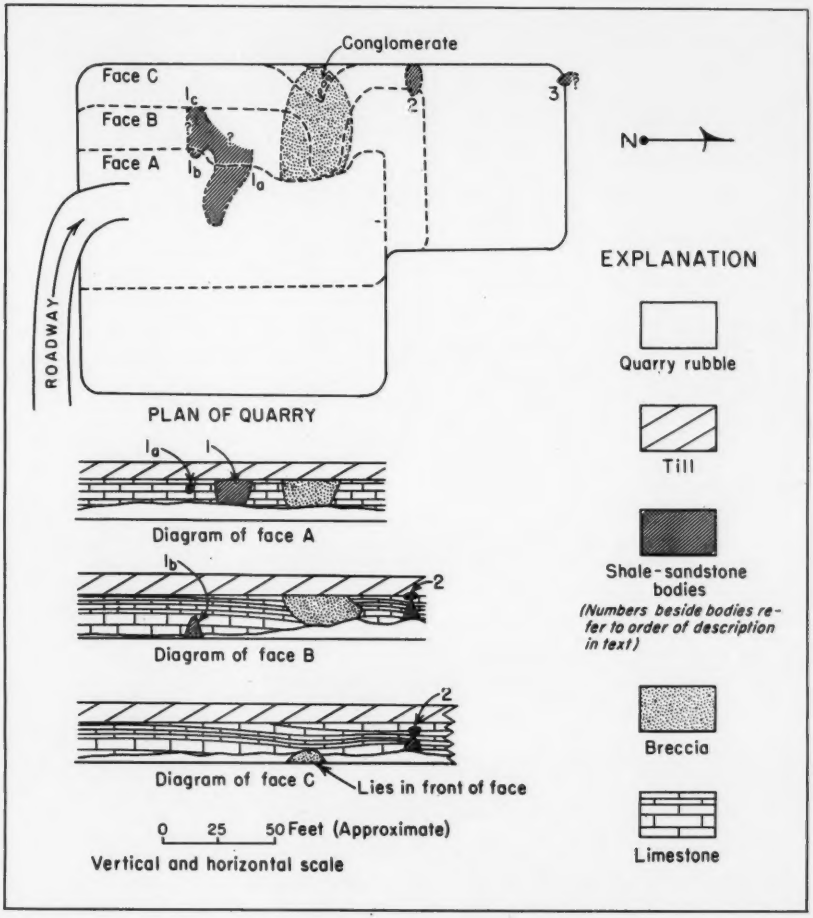

FIG. 2.—Sketches showing interrelationships of breccia, cave fillings, and bedded limestone at progressive stages of quarrying. Dashed lines indicate successive positions of face of quarry; dotted lines show reconstructed outlines of breccia and shale-sandstone bodies.

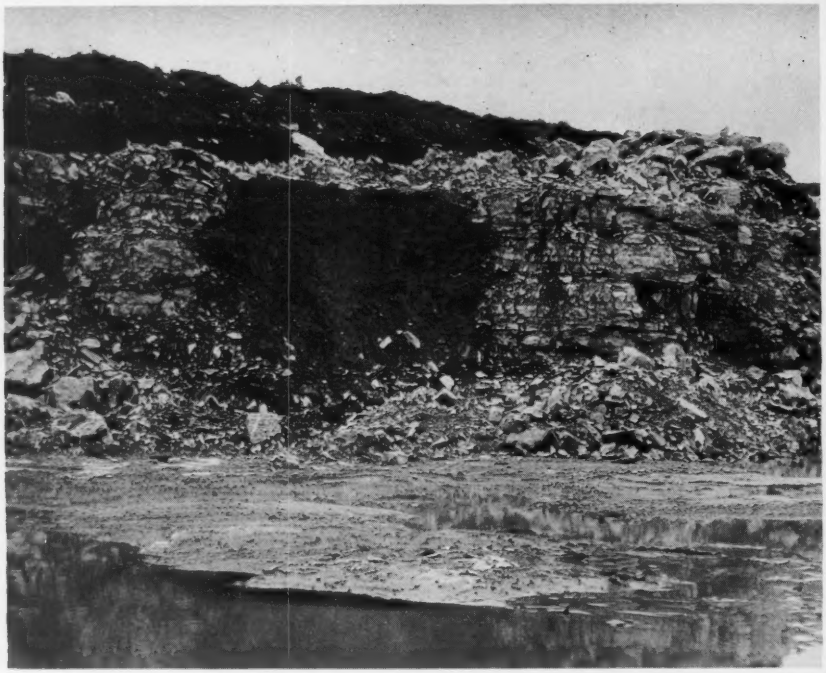

FIG. 3.—Quarry face A (see fig. 2) showing small body of shale and sandstone (left center), a similar, larger body (center), and part of the breccia body (extreme right), all in contact with normally bedded St. Louis Limestone. Floor of quarry (bottom center) contains sandstone wedge extending out from main shale-sandstone body. Limestone face is about 17 ft high.

along the east-west axis of a small synclinal fold. The St. Louis Limestone in the 30-ft interval between the breccia and the third shale-sandstone body dipped 20° S. 10° W. into the breccia. Reversal of dip occurred approximately halfway between the breccia and the northern shale-sandstone body and formed a small anticline. Dips of 30° N. 60° E. were measured on the north flank of this structure. At the stage of quarrying where these structures were most perfectly developed the breccia was reduced to a width of 15 ft from a previously observed maximum width of 32 ft. In the east wall of the quarry, opposite the features under discussion, the limestone beds are undulatory. Elsewhere in the quarry the St. Louis Limestone is in normal attitude.

The beds in the lower part of the quarry are about twice as thick as the beds in the upper part. Because the rocks dip toward the breccia, the thicker bedded limestone occupies about two-thirds of the face at the south end of the quarry but only about one-third of the quarry face adjacent to the breccia.

BRECCIA BODY

Description

The boundary between the bedded limestone and the breccia was abrupt (figs. 4, 5). In cross section the breccia body was crudely funnel shaped and was sharply reduced in width adjacent to the thicker limestone beds at the base of the quarry.

The breccia fragments were very angular (even jagged) to subangular and ranged in size from pebbles to 6-ft long slabs broken from single beds (fig. 6). The breccia fragments generally consisted of very fine-

grained light-brown to gray limestone which contained scattered medium-sized calcite crystals, a few rounded quartz sand grains, and some masses of pyrite, particularly near the edges of the fragments. The fragments were coated with finely laminated calcareous siltstone a few tenths of a millimeter thick; this siltstone was slickensided. The term slickenside is used in this report because it describes the physical appearance of the surfaces; the breccia is believed not to be fault breccia as discussed later. Thin ridges on the slickensides trailed out behind small pyrite crystals which projected from the breccia fragments. These ridges apparently were preserved by the protective action of the pyrite crystals as the breccia fragments rubbed against each other. The face of one large slab of limestone consisted of more than 4 sq ft of slickenside; this face appeared to have been a bedding plane.

Surfaces of some of the breccia fragments resembled stylolitic surfaces. The greatest number of breccia fragments displaying such surfaces were fist sized, but some were larger. Other evidences of differential solution were present on faces of both breccia fragments and undisturbed limestone beds in the quarry. Some of these faces were etched differentially into soft corrugations which simulated the folds of a window drape or the uneven surface of flowstone or dripstone in a cavern. All such surfaces observed in the Harris quarry, however, are believed to be the result of solution of the limestone and not the result of deposition of carbonate.

About 6 in of highly contorted laminated calcareous siltstone was found at the south edge of the breccia (fig. 5). Similar material formed the matrix of the breccia and in

FIG. 4.—Quarry face B (see fig. 2) showing bedded St. Louis Limestone (dipping north) in contact with chaotic breccia. Five to 10 ft of Wisconsin clay till (capped by overburden dump piles) present above limestone face. Photo taken after shale-sandstone bodies of figure 1 had been removed.

FIG. 5.—Closeup of part of figure 4 showing details of contact between bedded massive limestone (left center) and breccia (upper right). Small mass of breccia (lower left) adheres to face of bedded limestone. Banded siltstone (just above hammer and upper left), some of which is contorted (upper left), separates bedded limestone and breccia.

places was contorted around breccia fragments. The matrix material consisted of banded gray-green siltstone and fine-grained white to light-tan sandstone. The sandstone and siltstone were in thin bands 1 to 10 mm thick. Small pyrite crystals (less than 0.5 mm) were concentrated in sandstone bands. Much of the matrix was contorted, as the curved and sinuous attitude of the bands showed. The banding of the matrix was in all possible attitudes and in places was vertical. The fragments and matrix were intermixed thoroughly.

Origin

Breccias in the lower part of the St. Louis Limestone in Putnam County and adjacent counties have been documented by Reeves (1922, p. 240–243) and by Bieber (1959, p. 265–267). The data are not sufficient to eliminate all possibilities which can be postulated for the origin of the breccia in the Harris quarry. One of these possibilities, however, appears to the authors to be somewhat more plausible than the others. The key pieces of evidence bearing on the origin of the breccia are (1) the limited and abrupt lateral extent of the deposit, (2) the contorted and near-vertical attitudes of the laminated silts and fine sands of the matrix, (3) the thorough mixing of the matrix and fragments, (4) the presence of a saprolite between the limestone and till, and (5) the slickensides on some surfaces of the fragments. Origins suggested by one or more of the above pieces of evidence include (1) brecciation as a direct consequence of tectonic movements, (2) brecciation resulting

from a static load of ice or rock, (3) solution of evaporites and collapse of overlying rock, (4) collapse of the roof of a cavern, and (5) slumping induced by tectonic movements.

The possibility that the Mt. Carmel Fault passes near by was discussed by Melhorn and Smith (1959, p. 6). The deposit cannot be fault breccia, however, because there is no evidence of displacement of beds. Some of the breccias in the Joplin zinc-lead district (Missouri) were formed as a result of horizontal thrusting (Smith and Siebenthal, 1907, p. 9), but evidence for a similar origin does not exist for the Harris quarry breccia.

The saprolite precludes extensive glacial erosion at the quarry site and is indicative of a relatively thin cover of glacial ice. Furthermore, if it were assumed that the breccia formed as the result of collapse of a cavern roof, the quantity of breccia suggests that the original cavern roof would have been thick enough to hold any conceivable load of ice distributed over the relatively narrow breccia cavity.

An origin based on solution of evaporites and collapse of the roof of a resulting cavern can be discounted for the Harris quarry breccia. Collinson and Swann (1958, p. 13) suggested that breccias in the lower part of the St. Louis near Alton, Ill., are the result of solution of underlying evaporite deposits and subsequent collapse of the overlying rock. The breccia at the Harris quarry and other breccias present in Putnam County are found at and below the evaporite zone of the St. Louis Limestone, however, and have been observed in areas where only minor quantities of evaporites are present between undisturbed beds. The matrix of the Putnam County breccias consists of detrital sediments which appear to have moved

FIG. 6.—Closeup showing details of breccia pictured in figure 4. Note chaotic nature of breccia fragments and abundance of fine-grained matrix material. Hammer (lower center) gives scale.

into place in an unconsolidated state contemporaneously with the fragments, whereas some of the matrix in the Illinois breccias consists of sparry calcite which was precipitated later. The presence of unruptured limestone beds laterally adjacent to the Harris quarry breccia and other Putnam County breccias is final proof that the evaporite solution-collapse theory does not apply to these breccias.

It could be postulated that the breccia was formed by collapse of the roof of a cavern which originated by means other than evaporite solution. The cavern could have been formed by differential solution of limestone or by arching apart of competent limestone beds by tectonic forces as described by Weidman (1932, p. 42) for the Miami-Pitcher zinc-lead district in Oklahoma. Collapse material is present in many present-day caverns. The slickensides found on many of the fragments could have resulted from differential movement under pressure during or after collapse of a cavern roof or during arching of the beds. Furthermore, close physical association of the breccia with the shale-sandstone bodies, which subsequently will be demonstrated to be cavern fillings, suggests that the breccia also may be a cavern filling. Dripstonelike surfaces on many breccia fragments show that some differential solution has taken place. Differential solution could have occurred any time after the fragments were in place, however, and did not necessarily occur in association with the formation of a cavern. Perhaps the most serious objection to the cavern-collapse origin is that it leaves unexplained both the contortion of the matrix and the thorough mixing of matrix with fragments.

Brecciation of lithified St. Louis Limestone during a time of submarine slumping appears to be a plausible mechanism for the origin of the breccia. Slumping could have been initiated by tectonism, by storm surges, or by instability caused by static load on an initially dipping sea floor. Because the breccia fragments are slickensided and are very angular, it is apparent that the limestone was well lithified before brecciation. Thus storm surges and gravitational instability because of initial dip of the sea floor probably are eliminated as sources of the considerable amount of energy required to brecciate the limestone to the extent observed in the Harris quarry (fig. 6). (See Bieber, 1959, p. 267.) Forces caused by crustal instability, however, could have caused buckling and disruption of lithified limestone and could have initiated submarine slumping.

Some circumstantial evidence exists to support such a tectonism-slump theory. Melhorn and Smith (1959, p. 20) pointed out that the time of movement along the Mt. Carmel Fault cannot be determined precisely, but that it is later than the time of formation of the youngest beds (the lower part of the St. Louis Limestone) cut by the fault; they placed most of the movement in the interval from mid-Chester to mid-Pennsylvanian time. Forces necessary to fold and initiate slumping of the materials were available, however, if the earliest movements associated with the Mt. Carmel Fault took place during early St. Louis time. According to this theory, brecciation must have occurred during St. Louis time before deposition of the shale and sandstone bodies took place.

Any origin postulated for the breccia also must take into account the contorted clay-silt matrix, which appears to have been emplaced in an unconsolidated condition. The separation of the clays, silts, and fine sands of the matrix into bands suggests that the matrix had been deposited previously as bedded sediments. Siltstones, shales, and argillaceous limestones in the lower part of the St. Louis elsewhere in Indiana, both above and below thin limestone breccias, are evidence that sources of such matrix material were available. If these fine-grained materials remained plastic after lithification of overlying or underlying carbonate sediments, they could have acted as skid plates for the lithified carbonates. Lithification of carbonate sediments above unlithified clastic material possibly could be explained as a result of subaerial desiccation on a tidal flat. Evaporite deposits and ripple marks in the lower part of the St. Louis Limestone elsewhere in Indiana indicate that the sea was very shallow and that at times it could have been absent in some places, possibly allowing subaerial desiccation.

Multiple breccias in the St. Louis Lime-

stone have been observed in cores obtained from the SW¼NW¼ sec. 16, T. 13 N., R. 5 W., and from the NW¼NW¼ sec. 29, T. 14 N., R. 4 W., Putnam County. These locations are respectively 14 miles southwest and 8 miles south-southwest of the Harris quarry. In contrast to the Harris quarry breccia, the breccias in the cores are thin and are composed of small fragments of limestone in a calcareous matrix. Similar breccias previously have been ascribed by Bieber (1959, p. 267) to either submarine slumping or storms. It is possible that these smaller fragments have been transported downdip from high-energy loci of disturbance, similar to the one postulated for the Harris quarry. The occurrence of thin breccias at more than one stratigraphic position in the St. Louis may indicate that the disturbance which is postulated to have caused the brecciation at the Harris quarry was one of a series of pulses during early St. Louis time.

It should be pointed out that one objection exists to a tectonism-slump theory which will not allow unequivocal adherence to this type of origin for the Harris quarry breccia. The breccia appears to be abruptly limited in lateral extent (fig. 2)—a condition which should not be expected if the breccia were part of a widespread submarine slump phenomenon. It is possible, however, that the breccia of the Harris quarry is a restricted slump feature that has less confined counterparts elsewhere.

It appears likely that a combination of factors operated to cause the brecciation in the Harris quarry. Crustal movement may have provided the forces which caused brecciation of the lithified carbonates. The rock probably was set in motion on plastic muds which acted as slide planes. In the ensuing chaos, moving rock gouged down into underlying materials, and coherent units of the plastic mud became mixed with and contorted around the broken limestone fragments to form the matrix observed.

Although the details observed in the Harris quarry are not sufficient to demonstrate conclusively a mode of origin for the breccia, the authors believe that the theory of tectonic activation of submarine slumping is supported by more evidence than are other theories. This theory also may help explain the occurrence of widely distributed thin breccias in the St. Louis Limestone in Putnam County and adjacent counties.

SHALE-SANDSTONE BODIES

Description

Contacts between the shale-sandstone bodies and the St. Louis Limestone were sharp and irregular. Along these contacts, wedge-shaped cavities which tapered out into the limestone were filled by sandstone.

The largest shale-sandstone body consisted of three main sedimentary units (fig. 3). The lowest unit was unbedded light-gray fine quartz sandstone flecked with sand-sized crystals of pyrite; part of this unit is exposed at the present time in the floor of the quarry as a narrow wedge of sandstone extending eastward about 25 ft or approximately halfway across the quarry (figs. 2, 3). A productid brachiopod was collected from this unit; productids are especially abundant in Pennsylvanian rocks, but they range from Devonian through Permian. The middle unit consisted of dark-gray silty carbonaceous shale in beds 1 to 4 in thick that were deposited upon an inclined surface. The uppermost unit consisted of blocky, indistinctly bedded claystone and siltstone. Small pockets of kaolinite were associated with tiny euhedral pyrite crystals in this unit. Fragments of carbonized wood, partly replaced by pyrite, and a leaf fragment were collected from the upper unit. The leaf fragment has been identified as *Neuropteris*, a genus restricted in Indiana essentially to the Pennsylvanian. A limestone boulder, nearly 1 ft in diameter and coated by a ¼-in-thick armor of fine-grained crystals of pyrite, was imbedded in the uppermost unit. The lithology of the boulder connotes that the Salem Limestone, which lies below the St. Louis Limestone, may have been the source of the boulder.

A second and smaller mass (figs. 2, 3) contained dark shale similar to that of the top unit of the first mass and possibly was continuous with the larger mass. At this place a few inches of limestone overlay the shale.

At a later stage of quarrying a small triangular mass of sandstone was observed at the base of the quarry (fig. 7) just southwest of the former position of the largest shale-

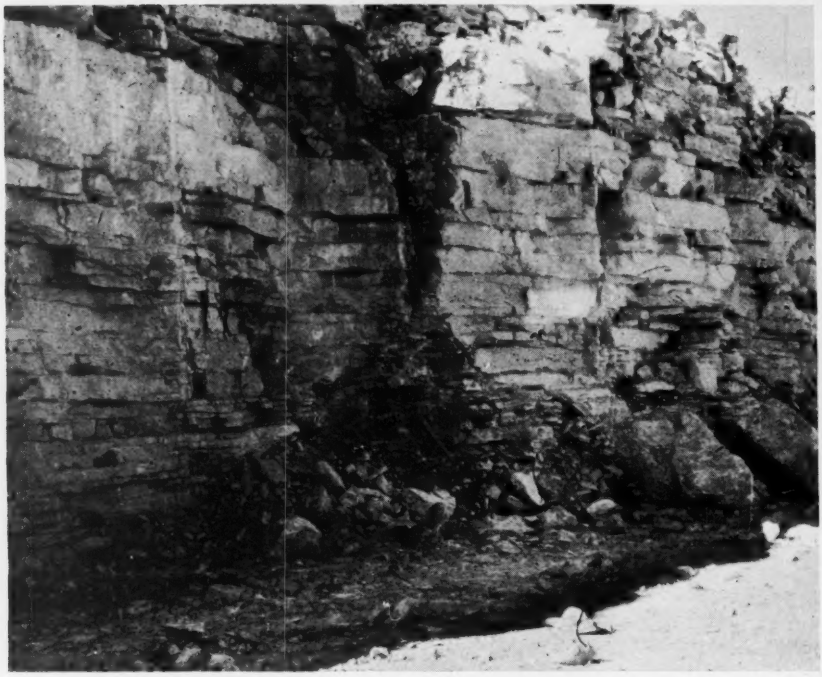

FIG. 7.—Quarry face B (see fig. 2) showing triangular body of sandstone (lower center) capped by St. Louis Limestone. This sandstone mass probably was connected with the shale-sandstone bodies shown in figure 1. Handle of pick (on sandstone mass) is 15 in long.

sandstone body. The sandstone at this place was overlain by about 12 ft of St. Louis Limestone. This sandstone probably was connected (fig. 2) with the two shale-sandstone bodies just described.

The shale in the third mass (fig. 2) appeared to be structureless but was similar in color and texture to the shales of the other masses. At one place during quarrying the sandstone in this body appeared to be varved. At the last place of observation the sandstone was in thin beds which were draped over a lower shale mass and which thickened toward their edges. The shale above the sandstone contained a few boulders of limestone. A few inches of mud in a horizontal seam in the overlying limestone were connected to this shale-sandstone mass by a constricted mud-filled fracture in the limestone. The mud in the seam was deeply weathered and displayed relict horizontal bedding and structure. The fourth and smallest mass, located in the northwest corner of the quarry (fig. 2), was composed of shale similar to that found in the other three bodies.

Origin

The openings filled by the shale-sandstone bodies can be explained only as (1) channels cut by surface streams or (2) cavities formed by underground solution. The fills must be (1) alluvial and (or) colluvial deposits, (2) marine deposits, or (3) subterranean stream deposits.

Channels cut into Mississippian carbonate rocks are perhaps the most striking evidence in Indiana of an erosion interval between

the times of Mississippian and Pennsylvanian deposition. These channels, as well as other surfaces produced by erosion, commonly are filled or covered by conglomerates and by sandstones or shales very similar to the shales and sandstones observed in the Harris quarry. The shale-sandstone bodies in the Harris quarry, however, were capped in places by bedded St. Louis Limestone and thus did not occupy surface channels. This relationship indicates a subterranean origin for the cavities in which they were found.

The largest body contains cross-bedding (fig. 3) which, although poorly developed, indicates that moving water was the agent of deposition for at least a part of the sediment. The varved sandstone in the third body suggests possible seasonal variation in the flow of water through the cavern. Seasonal variation in flowage is common in present-day karst areas. Postulation of post-St. Louis sinkholes or swallowholes connected to a system of underground caves and passageways best accounts for the present size, shape, and distribution of the cavities filled by the shale and sandstone.

Submarine currents from an arm of a shallow Pennsylvanian sea may have deposed sand and finer materials derived from nearby land in the cave. A similar origin was postulated by Smith and Siebenthal (1907, p. 8, 9) for the material that fills fossil karst features in Missouri. It is more reasonable to suppose, however, that such a cavern would have been at least partly filled by material previously brought in by streams and slope wash before a larger body of water encroached upon its environs.

The most logical explanation for the fill is that clay, fine sand, and organic debris were transported by small Pennsylvanian-age streams or sheet wash into the portal of a cavern system. Low-volume flowing water caused fine sands to be first deposited in the bottom of the cavities. This was followed by intermittent ponding of water and the consequent deposition of silt and clay-size material. At times renewed flow brought in coarser materials, which were washed into crevices or were deposited as small bars along the sides of the cave.

This hypothesis does not fully account for the dip of the beds in the shale (fig. 3). The writers conclude that the cross-bedded appearance of the body is the result of deposition of fine-grained material of the middle unit upon what must have been an inclined surface of the base unit; this deposition was followed by mild erosion and truncation of the middle unit. Sedimentation was completed by deposition of the upper unit in a more horizontal attitude. The boulder, the brachiopod, and the leaf probably were washed in by streams or perhaps merely fell in under the influence of gravity.

The Pennsylvanian cave deposits in the Harris quarry are about 5 miles east of the main Pennsylvanian outcrop belt in this part of Indiana (fig. 1). A comparable outlier in the abandoned Midwest Rock Products Corporation quarry at Greencastle, Putnam County, is about 7 miles due south of the Harris quarry and likewise about 5 miles east of the main Pennsylvanian outcrop. (See fig. 1.) Pennsylvanian shale in the Midwest quarry (Malott, 1952, p. 23–24) is similar in general appearance to the shale found in the Harris quarry and lies on a much eroded surface of the Ste. Genevieve (middle Mississippian) Limestone.

Another solution feature filled by shale similar in general appearance to the shale in the Harris quarry was reported by Esarey and others (1950, p. 18). The feature was located within the general outcrop belt of Pennsylvanian rocks in the abandoned Wallace quarry (more recently known as the Cumberland quarry), northeastern Parke County, Indiana, about 20 miles northwest of the Harris quarry (fig. 1). This shale body, situated in the Salem and Harrodsburg (middle Mississippian) Limestones, contained coal and was dated as Pennsylvanian. The Wallace quarry shale, like the shale-sandstone bodies of the Harris quarry, has been removed in quarrying operations.

DESCRIPTION AND ORIGIN OF CONGLOMERATIC MATERIAL

Some conglomeratic material overlay the breccia at its westernmost exposure (fig. 4). This conglomerate presents a special, perhaps separate, problem. The conglomerate was directly overlain by Pleistocene till and was laterally adjacent to and was directly

underlain by Mississippian St. Louis sediments. The nature of the contact of the conglomerate with surrounding material could not be ascertained, except that it appeared to rest upon an erosional or solutional surface on the St. Louis Limestone. The framework of the conglomerate consisted of subangular to rounded pebbles of partly silicified very fine-grained limestone and medium- to coarse-grained calcarenite. The pebbles were enclosed in a fine- to medium-grained quartz sandstone matrix similar in composition to the sandstone found in the largest shale-sandstone body. (See p. 11.)

Such sandy conglomeratic material is unknown in the St. Louis Limestone elsewhere in Indiana. Because the angularity of the pebbles and the lithology and grain size of the matrix were greatly different from that of comparable components of the breccia, the authors believe that the breccia and the conglomerate are not of the same age or origin. Similarly, because the conglomerate was well consolidated and because the lithology of the conglomerate did not match that of Pleistocene materials in this area, the authors believe that the conglomerate is not of Pleistocene age.

Materials similar to this conglomerate are exposed at various localities in Putnam County and adjacent counties (see, for example, Malott, 1952, p. 23, 26, 33, 35, 36, 37) in the Rosiclare Member of the Ste. Genevieve Limestone and at the base of the Paoli Limestone. For the conglomerate to have been deposited on the lower St. Louis Limestone (and breccia) of the quarry during middle Ste. Genevieve (Rosiclare) or Paoli time, however, would have required a long period of preconglomerate erosion in Ste. Genevieve time. Evidence for such a period of erosion is completely lacking in Indiana.

Prominent erosion surfaces were developed in Indiana between the Mississippian and Pennsylvanian and between Pennsylvanian and Pleistocene deposition. The conglomerate probably rests on one of these surfaces and thus could be late Paleozoic, Mesozoic, or Tertiary in age. However, since the matrix of the conglomerate resembles very closely the sandstone of the basal member of the largest shale-sandstone body, it is locigal to assume that there is a genetic connection between these two deposits. Therefore, although quartz pebbles characteristic of most conglomerates in the lower part of the Pennsylvanian in Indiana are lacking in this deposit, the authors believe that the matrix of the Harris quarry conglomerate was derived from the same source as that of the shale-sandstone bodies and that the conglomerate was deposited at the same time as these bodies. Deposition probably took place during Pennsylvanian time on a subaerial erosion surface that was formed on the St. Louis Limestone and on the breccia.

SUMMARY

It appears that the breccia and the shale-sandstone masses, which are coincidentally in close physical proximity, are the results of two separate events which occurred at two different times. The evidence is not sufficient, however, to provide complete proof of how these events took place. The authors believe that subsequent to deposition of more St. Louis Limestone than is now present in the Harris quarry a disturbance which folded and brought about slumping and brecciation of the bedded and lithified St. Louis Limestone occurred in this vicinity.

Differential solution of carbonate rocks took place during the erosion interval between the time of deposition of Mississippian and Pennsylvanian sediments and resulted in the formation of small caverns coincidentally near the breccia. When sedimentation was resumed in Pennsylvanian time the small caverns at the Harris quarry were filled with fine quartz sand, silt, clay materials, and organic debris. These filled cavities demonstrate that a karst terrain was formed on Meramecian limestones and partly preserved prior to the more recent development of the extensive karst topography now present in these same Meramecian limestones of southern Indiana.

Although the exposures in the Harris quarry represent very small amounts of space and time, the authors believe that the above interpretation of their mode of origin adds to the present knowledge of the geologic history of a part of the Illinois Basin.

ACKNOWLEDGMENTS

The authors wish to thank Mr. Roy Harris, President of Harris Stone Services, Inc., and his sons for their many courtesies. Several of our colleagues at the Indiana Geological Survey gave helpful criticisms of the manuscript and thoughtful suggestions concerning our ideas on origins.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 31, NO. 2, pp. 288–300
FIGS. 1–3, JUNE, 1961

NOTES

SPRING DOMES DEVELOPED IN LIMESTONE[1]

IAIN A. WILLIAMSON
Wigan and District Mining and Technical College, Wigan, England

ABSTRACT

A group of dome shaped features in Lower Carboniferous (Mississippian) limestones in Northwest Lancashire, England are described. Radial jointing is crudely developed and many of the features are characterised by a central crater. No such features have been previously described; they are interpreted as non-diastrophic structures developed by the expulsion of water from an underlying source. The descriptive term "spring-dome" is suggested for the structures.

INTRODUCTION

The structures described are located about High Water Mark on the foreshore, some 300 yards south of Cart Lane Railway Crossing, Grange-over-Sands, in Northwest Lancashire, England. The National Grid Reference to the locality is SD402763. Along this part of the shore, limestones in the lowest beds of the Upper *Dibunophyllum* subzone of the Lower Carboniferous (Mississippian) form a continuous outcrop (Garwood, 1912, page 529 and Plate LV). The features are exposed within an area approximately 200×20 yards, over which the limestones have a markedly irregular surface and visibly may be separated into two beds, a lower creamy limestone and an upper white limestone. (The use of the noun limestone is taken to embrace that group of carbonate rocks composed largely of calcium carbonate.) Both beds are organic fragmental limestones extremely rich in foraminifera, bryozoa, and macro-shell fragments.

Upon a bedding surface of the upper limestone are more than 30 circular or elliptical mounds, most of which have a central hollow or crater, (fig. 1). The craters are often rendered more prominent by their darker colouration than that of the rest of the limestone forming the features. The dimensions of whole features and craters are variable and exact measurement is difficult owing to the elliptical nature of certain of the features and also the very irregular surface on which they occur. Upon some of the larger mounds two craters are developed. Altogether fifteen mounds occurring in an area of 20 sq yards were measured. Their dimensions are shown in table 1. Where an elliptical mound or crater was measured two diameters are given, the greatest and the least. None of the measurements made bear any constant relationship to any others.

The lower creamy limestone is well jointed whereas the upper bed, that in which

TABLE 1.—*Dimensions of features. Measurements in inches are only approximate*

Diameter of Feature	Height of Feature Above General Surface of Limestone	Diameter of Crater	Depth of Crater from Rim
44	16	18×10	10
23	9	11	8
24	7	C.A.	C.A.
38×31	9	13	13
38×24	6	13×8	10
36	12	6×3	6
36	10	C.A.	C.A.
39	8	12	9
42×32	9	10	9
39×24	10	11×8	9
45×37	8	9	6
47	12	9	8
		8	7
44	12	18	10
56×36	6	C.A.	C.A.
40×31	7	12×7	12
I.F.	I.F.	12	8
I.F.	I.F.	12	8
I.F.	I.F.	15×12	18

C.A. = Crater Absent.
I.F. = Irregular Feature.

[1] Manuscript received April 8, 1960.

FIG. 1.—Spring dome developed in Carboniferous Limestone showing crude radial jointing and deep central crater. Size of film carton—3 in.

the features occur, shows little obvious jointing in the bed as a whole (fig. 2). Upon some of the mounds themselves, however, a distinct radial jointing is seen, (fig. 1).

ORIGIN OF THE STRUCTURES

No such structures in limestone have been previously described. There are, however, certain others, described from other sediments, which bear some external resemblance to the Grange features. Most noticeable are the sand volcanoes recently described from the Namurian of Eire (Nevill, 1957, p. 320–322; Gill and Keunen, 1958, p. 441–456), and attributed to the extrusion of sediment laden water from slumped masses prior to the normal deposition of the overlying bed. Many of these have similar dimensions to the Grange features and also are elliptical in plan (Nevill, 1957, p. 321). However, the internal structures differ, for at Grange the lithology and grain size are constant throughout the features whereas the sand volcanoes show well developed lamination and possess in most cases sedimentary pipes or feeders.

The writer has recently described a spring pit in littoral muds (Williamson, 1960). In a depression about 4 in deep and 3 ft across were several conelets a few inches in diameter. The conelets were building up from loose material erupted from small springs at the base of the depression.

Other externally similar structures though on a smaller scale are the "pit and mound" structures described by several authors and summarized by Shrock (1948, p. 132–138). These minute craters and sometimes mounds are attributed to water currents moving vertically upward through settling suspensions of mud. They have been discovered in both modern and ancient sediments.

None of the above structures, though bearing external similarity, can be genetically related to the Grange features. It is im-

FIG. 2.—The limestone in which the features are developed and the underlying regularly jointed and darker limestone.

possible to attribute the features to the piling up of an incoherent deposit around the mouths of craters or springs, for the radial jointing in an elevated deposit could only be formed in a coherent sediment. Similarly, it is improbable that the features were caused by the burrowing activities of some marine animal since their extremely localised occurrence requires the supposition of a very rare and hitherto undescribed Carboniferous burrowing animal.

Since the structures under review cannot be related to any previously described structures, the writer tentatively suggests the mode of formation described below. As a result of this note similar features may be discovered elsewhere which may, as a result of more perfect preservation, be interpreted in a different way.

It is considered that the features result from the expulsion of water from a semi-rigid sediment. A sub-aqueous environment is suggested by the fauna of the limestone and also from the lack of any drainage channels running down the slopes of the features from the craters. For such channels may be expected if the features were of sub-aerial origin (Quirke, 1930).

A most significant feature is the radial jointing which is peculiar to the features and may therefore be presumed to have a common origin with that of the features themselves. Such jointing would form as a result of a vertically directed upward force in a consolidated or partly consolidated deposit. It is considered that this force was effected by local concentrations of water moving vertically upward through the limestones and prior to the deposition of the overlying bed. No concentric joints are developed around the features. The presence of open craters in the bed suggests an actual orifice to the springs and therefore the absence of any overlying deposit. Clearly the limestones must have been in a partly consolidated state since, if otherwise, collapse would have occurred on the cessation of the waterflow. The water may have been derived from the underlying creamy limestone acting as an aquifer or from connate

water expelled from that bed during compaction. The extremely localised occurrence of the features suggests a local physiographic low at the time of formation.

The mounds with double craters probably resulted from the coalescence of two formerly isolated features which became mutually interfering and now appear as one discrete mound. Many domes in the area lack craters and presumably the upward surge of water lacked the power to rupture the limestone.

The discolouration of the craters is considered because of submergence during High Tide. Small pools of sea water remain trapped in many of the craters after the retreat of the tide, and it is in these craters that discolouration is most obvious. A similar effect is also noticeable in adjacent areas along the shore wherever small pools of water are held up in chance irregularities in the limestone. No evidences of feeder pipes below the craters have been observed, the limestone both forming the features and that below being of similar lithology. The craters may have been formed by the erosional effects of the springs. Any cylindrical pipe-like structure at the base of the craters, such as that described by Gabelman (1955), would have been destroyed during the subsequent recrystallisation of the limestones. Around the orifices of certain craters there is some evidence of recent solution, but it is not considered that the craters resulted in this way. Unfortunately, since there is a marked absence of any diagnostic sedimentation structures in the limestones comprising the features, their exact origin must remain open to question.

The term "spring dome" is suggested for the features, since it is considered that they originated by the doming of sediment because of epigenetic springs.

ACKNOWLEDGMENTS

The author is indebted to his wife for assistance in the field and to Dr. J. E. Hemingway for helpful criticism of the paper.

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A SIMPLIFIED METHOD FOR DETERMINING RELATIVE ENERGIES OF DEPOSITION OF STRATIGRAPHIC UNITS[1]

GLENN S. VISHER
Sinclair Research Laboratories, Inc. Tulsa, Oklahoma

In the exploration for oil the emphasis has more and more been on the discovery of stratigraphic traps. Many mapping techniques have been described for delimiting areas of rapid facies change and consequently optimum areas for exploration. In many instances, however, a sand/shale ratio map or a number of sands map does not yield information on the nature of potential reservoir rocks. A certain minimum energy is required to transport and sort the clastic fraction to make a reservoir an economic exploration objective. One method of obtaining this information is to collect cores

[1] Manuscript received May 2, 1960.

TABLE 1.—*Transport velocities for various sizes of particles*

Water Velocity in cm/sec	Size Groups in mm
300 cm/sec	Greater than 16.0 mm coarse cgl.
100 cm/sec	Less than 16.0 mm fine cgl.
10 cm/sec	Less than 2.0 mm coarse ss.
5 cm/sec	Less than 1.0 mm medium ss.
1 cm/sec	Less than 0.1 mm fine ss.
0.5 cm/sec	Less than 0.05 mm siltstone

and samples from a large number of wells and surface outcrops, make detailed physical analyses of the sand distribution, and construct maps of the mean grain size and sorting. This gives clear and concise information on areal variations in the reservoir, but in most instances cores are not available or oil company personnel do not have the time necessary to obtain this information.

Another method, more easily applicable to oil exploration, is the utilization of the coarsest size fraction as an index of the minimum energy required to transport and deposit clastic detritus. A method that the writer has found to be practicable is based on a diagram devised by Hjulstrom (1939).

In this diagram transport and erosion energies are shown for clastic particles of all sizes in relation to various water velocities. The minimum transport velocity for various grain sizes were used as energy values. Table 1 gives a list of the values.

By using the velocity values directly, a minimum value of the energy of the depositing medium can be determined. To calculate the energy value for a section of rocks it is necessary to tabulate the percent of the section that occurs in each of the above groups and multiply this percent by the value of the water velocity. A simple addition of the resulting values will give an average energy value for the section. Table 2 illustrates the procedure.

One limitation of this procedure is that it does not take into consideration sorting, which also reflects the energy of the depositing medium and likewise is very important in the determination of permeability. Without complete physical analyses only a very qualitative approximation of the sorting is possible. In addition to the technique outlined above it would be worthwhile to estimate the degree of sorting and note this alongside the energy value. In most shelf-deposited sediments a correlation typically exists between sorting and grain size, and neglecting sorting would not introduce appreciable errors.

Facies maps based on sand/shale ratios also outline, in a broad way, high energy areas. The use of the technique outlined here, however, is not restricted to differentiating sand from shale but will yield information on the nature of the sand. The value of this can readily be illustrated; for example, in a sheet sand which was deposited under regressive marine conditions there may be linear bar trends within the sand body, and these bar trends would contain sands deposited at a higher energy. Another example would be a large deltaic plain in which the distributary channels contain sands deposited at higher energies than the enclosing sand. In both instances under the proper hydrodynamic conditions, stratigraphic traps would be present, and the technique described here would offer a method for locating these traps.

It is difficult to divorce provenance from any system of calculating energies. In this system there probably would be a correlation between high energy areas and provenance areas. This might indicate that energy was highest near the source, or it might be a

TABLE 2.—*Example of calculation*

Size Group	Energy Value	Percent of Section	Col. 2×Col. 3
Coarse cgl.	300	.00	0.0
Fine cgl.	100	.02	2.0
Coarse ss.	10	.05	0.5
Medium ss.	5	.45	2.25
Fine ss.	1	.25	0.25
Siltstone	0.5	.10	0.05
Clay	0.0	.13	0.00
			5.0 cm/sec

result of a limited supply of coarser detritus. Because of this limitation it would be necessary to use other mapping techniques to gain a fuller understanding of the sediment distribution in the areas of interest. Certainly net sand, number of sands, and other facies mapping techniques would yield the necessary information to determine those areas where sediment was deposited under high energy conditions, and those areas which contain coarse detritus only because of proximity to source areas.

Energy maps can be constructed for a wide variety of stratigraphic units, the only requisite being the assurance of stratigraphic equivalence of the mapped unit.

The advantages of this type of map, briefly summarized, are as follows: (1) maps can be used to evaluate reservoir characteristics (grain size correlates with permeability); (2) map can be used directly as an exploration tool when production is found in areas with a specific range of energy values; (3) map gives information on environments of deposition of clastic bodies; (4) data can be obtained from well cuttings and/or surface samples; (5) calculations are not complicated; and (6) map would aid in delineating source areas of clastic detritus when used in conjunction with other maps.

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CONCERNING THE ASSOCIATION MONTMORILLONITE-ANALCIME IN THE SERIES OF STANLEYVILLE, CONGO[1]

JEAN-PIERRE VERNET
University of Lausanne, Switzerland[2]

The mineral associations to be described are in formations of late Jurassic (Kimmeridgian) age, Stanleyville, ex-Belgian Congo. There is an alternating series of sandstone and shale with several horizons of bituminous schists.

Thirteen samples of shales from four borings south of Stanleyville have been studied. These borings are several tens of kilometers distant from one another. All samples have been taken from between 7 and 39 meters of depth. Although pertaining to different lithological subdivisions, the mineralogical composition of their fine fraction are very akin. The recorded differences seem rather to be linked to a difference in the degree of alteration of these rocks.

The X-ray study of oriented aggregates and of powders showed that the clay fraction is essentially montmorillonitic. Illite in small amounts always accompanies this montmorillonite. Two samples have revealed the presence of a trace of kaolinite. In the others, in addition to the montmorillonite and illite, either analcime or a mineral represented by a peak at about 10.5 Å are found. Dolomite, feldspars, and quartz are visible in the diagrams of powders.

Despite the small number of samples studied and the lack of geological data, a certain number of interesting conclusions can be stated.

Among the seven samples of two borings, montmorillonite is present in mixed-layers with illite. It is accompanied by a mineral whose presence is revealed by a peak at 10.5 Å, a peak which is poorly differentiated from that of illite. This peak could be attributed to hydrobiotite or to attapulgite. Electronmicrographs show a cluster of fibers in two of the cuts which suggest attapulgite. This determination is doubtful because of the very small amount present. The presence of

[1] Manuscript received May 18, 1960.
[2] Formerly Post Doctoral Fellow, University of Illinois.

any attapulgite in these beds is probably detrital.

In the six samples of the other two borings, montmorillonite is absolutely normal; in addition to illite, it is accompanied by analcime. This zeolite appears especially in the diagrams of powders; it is of a larger size than the size of clay minerals. These clays with analcime have a characteristic apple green color very likely caused by the presence of a certain proportion of analcime.

The determination of analcime was made on the diagrams of powders. This mineral is very well crystallized. All the reflections included between 5.66 Å and 1.74 Å were obtained with intensities approaching very closely those given by the analcime of Golden, Colorado (A.S.T.M. Card). (Fig. 1)

Analcime is present in five of the six samples containing normal montmorillonite.

Analcime is a relatively uncommon mineral in clays. Early works have pointed out its presence in sedimentary formations apparently free of material of volcanic origin (von Seebach, 1862; Guthe, 1863; Kloss, 1899). In the United States, analcime has been described in the Green River Formation, associated with material of eruptive origin (Bradley, 1929). Bradley thinks that this mineral was formed in place in a playa lake by the combined action of salts dissolved in lake waters and the products of the dissolution of volcanic ashes. Ross (1928), describing the rocks containing green analcime near Wikieup, Yavapai County, Arizona acknowledges the same genetic process while, at the same time, considering a second possibility—that is, the reaction of concentrated sodium salts with hydrated aluminum silicates in a playa lake. In a new study of the layers containing analcime of Yavapai County, Arizona, Ross (1941) states that these sediments settled in a playa lake and that the sodium salts coming from the dissolution of volcanic glass and ash formed the analcime and not the clay mineral, which

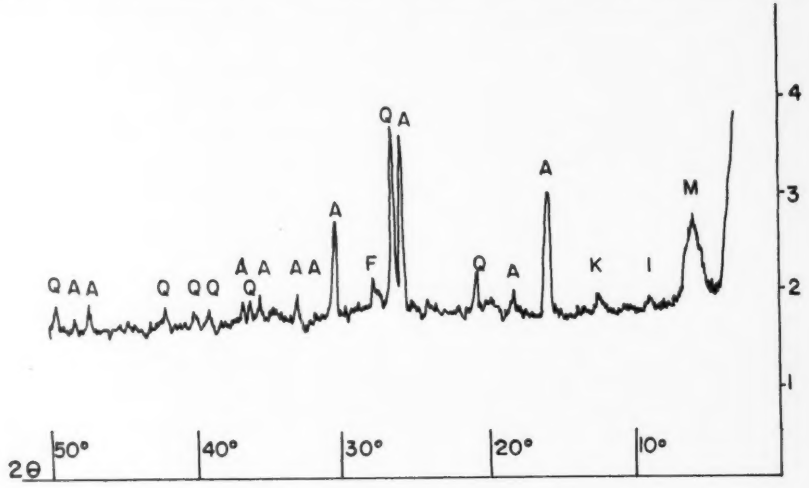

FIG. 1.—Representative spectrograph.

M: montmorillonite
I: illite (trace)
K: kaolinite (trace)
Q: quartz
F: feldspars
A: analcime

Spectrometer Norelco
Radiation Cu-Kα, λ = 5418 Å
Speed: 1°/min.
Filter: Ni
Color of the sample: greenish
Locality: 40 miles South Stanleyville (ex-Belgian Congo)

is the normal product derived from the destruction of these volcanic ashes. The origin of this analcime would be analogous then to that of the Green River Formation (Bradley, 1929); this is also the case of the analcime discovered three miles northeast of Reykjavik, Iceland (Tyrrell and Peacock, 1926). Lastly, analcime has been described in the Popo Agie Member of the Chugwater Formation in western Wyoming (Keller, 1952). Keller noticed that the substratum of the series of rocks containing analcime is a red shale with montmorillonite. There is no evidence that this montmorillonite comes from the alteration of products of volcanic origin. To Keller this analcime would have an origin identical to Ross' (1928) second hypothesis—that is, the reaction of concentrated sodium salts with hydrated aluminum silicates; the montmorillonite could very well supply the necessary silica and alumina. This genesis took place in a playa lake; the thickness of the layers containing analcime is approximately 30 meters. Only the zeolite beds of the Green River Formation attain this thickness. In this last formation analcime represents 16 percent by weight of the rock.

In the deep marine sediments collected by the *Challenger*, a zeolite accompanies volcanic debris (Murray and Renard, 1891).

The fuller's earth of Tehachapi, California, also shows an association of zeolite and montmorillonite (Kerr and Cameron, 1936).

In summarizing the information supplied by the literature concerning the origin of analcime, it appears that analcime generally comes from the products of the alteration of materials of volcanic origin. Only the beds studied long ago by von Seebach (1862), Guthe (1863), and Kloss (1899) and recently by Keller (1952) show a sedimentary origin excluding all relation with debris of volcanic rocks.

In the present study of the series of Stanleyville, the regional geology is not known completely, nor is the origin of montmorillonite known; therefore either hypothesis put forth by Ross (1928) may be applicable. However, in view of the literature, it seems that the presence of a large proportion of analcime in an essentially montmorillonitic rock is rather in favor of a volcanic origin of these sediments.

ACKNOWLEDGMENTS

The author is very grateful to Dr. R. E. Grim for his constant help during the investigation and the preparation of the manuscript and to Dr. Jean Lepersonne who provided the samples.

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FERRIC OXIDES IN RED BEDS AS PALEOMAGNETIC DATA[1]

FRANKLYN B. VAN HOUTEN
Princeton University, Princeton, New Jersey

Any specific conclusions about the magnetic properties of detrital sedimentary rocks must rely in part upon knowledge of the ferric oxide minerals present. Those in the coarser fraction of siltstones and sandstones may be (1) black detrital grains of inherited, relic oxides, or (2) grains of oxide produced by alteration of the relic black grains. Pigment minerals in mudstone and in the matrix of sandstone may be (3) inherited products of weathering in the source area, (4) some of which may have been altered after deposition. In addition, (5) red pigment, especially that coating grains and forming cement, may be chemically precipitated ferric oxide.

Of these genetically different ferric oxide minerals in red beds, only those inherited grains or weathering products that were oriented during sedimentation and those alteration products magnetized essentially at the time of deposition yield information about a geomagnetic pole position dated by the deposit.

BLACK GRAINS

Is the magnetism of the rock mainly in the black detrital grains? Are these grains magnetite and ilmenite or largely hematite? If they are hematite, were they produced by weathering in the source area, by alteration during transportation and deposition, or by alteration after burial? How long after burial?

Black ferromagnetic grains in the Precambrian Torridon Sandstone and the Devonian Old Red Sandstone (Creer, Irving, and Runcorn, 1954; Irving, 1957) and in the Triassic Keuper marl (Blackett, 1956, p. 53, 57) are mainly specularite (hematite) with intergrowths of ilmenite or leucoxene and small remnants of magnetite. Irving (1957, p. 101–103) believes that in the Torridon Sandstone these are relic grains that were statistically oriented in the earth's magnetic field during deposition and that they are the principal source of remanent magnetization of the rock. It is not known, however, whether the magnetic intensity of the grains is caused by the specularite itself or by the small quantities of magnetite which they appear to contain. On the basis of such observations, Runcorn (1959, p. 1005–1006) has recently claimed that the black detrital iron oxides in red beds as a general class are predominantly hematite, and that magnetite and ilmenite reported in red beds have been incorrectly identified.

Analysis of twenty nine red deposits ranging in age from Precambrian to Recent (table 1) reveals that in most specimens older than middle Tertiary at least 80 percent of the black grains are specular hematite, thus confirming Runcorn's conclusion. Moreover, in some rocks younger than Jurassic other black oxide grains occur in abundance with a general increase in rocks of Tertiary and Recent age. These data are preliminary results of a study of black detrital grains of iron oxide in red beds supported by a grant from the National Science Foundation (project G 14178).

The fact that ilmenite and magnetite predominate in these younger deposits and that grains of specularite and martite are not abundant in source rocks nor in analyzed laterites (table 1; see also Allen, 1948, p. 622; Eyles, 1952, p. 43), suggests that hematite grains in many red beds may be post-depositional alteration products derived from inherited grains of ilmenite and magnetite. Inasmuch as the conversion to hematite may have occurred long after burial, the remanent magnetization in the black grains may not be a measure of the earth's magnetic field at the time the red beds accumulated. The available data are as yet too few to warrent any attempt to explain them, however.

[1] Manuscript received May 25, 1960.

TABLE 1. *Composition of black ferromagnetic oxide grains in red deposits.*[1]

Age and Formation	Locality	Specular hematite	Magnetite ilmenite	Remarks
Recent				
Laterite	Central Cuba	s	D	
Red and yellow soil	SE Pennsylvania		D	Subordinate oxides not determined
Pliocene-Pleistocene				
Falca sand	Margarita, Venez.	s	D	
Late Tertiary				
Ferruginous bauxite	Oregon		D	Allen, 1948, p. 622
Antrim laterites	Northern Ireland		rare	Eyles, 1952, p. 41–43
Tuy Formation	N. Cen. Venezuela	D		Subordinate oxides not determined
Unnamed	St. Croix	D		Subordinate oxides not determined
Oligocene				
Tavera Formation	Dom. Republic	D		Subordinate oxides not determined
Parangula Formation	W. Venezuela	D		Subordinate oxides not determined
Eocene				
Galisteo Formation	N. Cen. New Mex.	D		Subordinate oxides not determined
Cretaceous				
Unnamed	Tierra del Fuego	D		Subordinate oxides not determined
Cloverly Formation	Central Wyoming	s	D	Volcanic-rich sandstone
Cloverly Formation	Central Wyoming	D	s	Mudstone
Jurassic				
Morrison Formation	NW. Utah		D	Subordinate oxides not determined
Entrada Formation	NW. Utah		D	Subordinate oxides not determined
Lak Member	Wyo., S. Dakota	D		Subordinate oxides not determined
Juro-Triassic				
La Quinta Formation	W. Venezuela	D		Subordinate oxides not determined
Triassic				
Brunswick Shale	New Jersey	D		Subordinate oxides not determined
Stockton Sandstone	New Jersey	D		Subordinate oxides not determined
Chugwater Formation	Cen. Wyoming	D		Subordinate oxides not determined
Chinle Formation	Utah, Arizona	D		Subordinate oxides not determined
Ankareh Formation	Northern Utah	D		Subordinate oxides not determined
Moenkopi Formation	Utah, Arizona	D		Subordinate oxides not determined
Keuper Marl	England	D		Blackett, 1956, p. 53, 57
Permo-Triassic				
Goose Egg Formation	NW. Wyoming	D		Subordinate oxides not determined
Permian				
Hoskinini Member	SW. Utah	D		Subordinate oxides not determined
Organ Rock Member	SW. Utah	D		Subordinate oxides not determined
Hermit Shale	Northern Ariz.	D		Subordinate oxides not determined
Pennsylvanian (?)				
Sabaneta Formation	W. Venezuela	s	D	Siltstone
Sabaneta Formation	W. Venezuela	D		Sandstone
Mississippian				
Mauch Chunk Formation	Cen. Pennsylvania	D		Subordinate oxides not determined
Devonian				
Old Red Sandstone	Scotland	D		Irving, 1957
Silurian				
Salina Formation	Cen. New York	D		Subordinate oxides not determined
High Falls Formation	NE. Pennsylvania	D		Subordinate oxides not determined
Ordovician				
Juniata Formation	Cen. Pennsylvania	D	s	
Proterozoic				
Freda Sandstone	Michigan	D	s	
Hakatai Formation	Arizona	D		Subordinate oxides not determined
Torridon Sandstone	Scotland	D	s	Irving, 1957

1. By x-ray analysis capable of detecting more than 20 percent subordinate oxides.
D—dominant oxides; s—subordinate oxides, probably constituting more than 20 percent of black grains. Where not determined subordinate oxides presumably constitute less than 20 percent of black grains.

APHANITIC RED PIGMENT

Is the magnetism mainly in the red pigment? Was most of the aphanitic ferric oxide inherited from the source area? Is it inherited hematite or is it mainly hematite produced by the aging of hydrohematite or some hydrated ferric oxide after deposition? Is there any goethite, lepidocrocite, or maghemite in the clay fraction? How do these affect the magnetization of the rock? Is any of the pigment chemically precipited hematite? What was its origin? Now long after deposition was it precipitated?

In view of the fact that magnetization of many red rocks apparently resides in the ferric oxide pigment (Blackett, 1956, p. 12, 48; Irving, 1959, p. 52), its nature and origin are significant in paleomagnetic investigations. Yet, there is no consistency of interpretation regarding its origin nor has evidence been adduced to support one or another assumption.

Hematite is known to be the principal pigment in most red beds tested (Steinwehr, 1954), goethite is also present in many, and maghemite predominates in a few red beds (Hofer and Weller, 1947; Bock, 1954, p. 155).

Many lines of evidence suggest that the pigment in the mud matrix of most red beds probably is a detrital product inherited from the source area. The presence of lepidocrocite, maghemite, hydrohematite, and goethite, in addition to hematite, in some red upland soils implies that any of these oxides may also be inherited in red sediments. Accordingly, investigations of the matrix minerals in red beds must consider this possibility.

Blackett (1956, p. 49) notes that some of the hematitic matrix of the Old Red Sandstone may have been derived from red soil. To the extent that this pigment was inherited from the source area and the magnetization of the rock is in the matrix hematite and question arises, "Is the susceptibility of hematitic clay high enough to produce an orientation of the hematite-coated clay platelets in the earth's magnetic field as they settled?"

Although the idea that pigment in red beds has been inherited essentially unaltered from red soils seems to be a reasonable explanation, it is not supported by meager records of recent tropical alluvium. Contrary to the implications of the proposition, there apparently is no *widespread* accumulation of bright red sediment in the tropics today. The lower Amazon River, though commonly said to transport red mud, actually has dirty yellowish-red water and light gray to gray-brown alluvium (Katzer, 1903, p. 45, 57; Sioli, 1957, p. 609), and the Senegal River in west Africa deposits yellow-brown detritus (Tricart, 1955). It should be noted, however, that these are large through-flowing rivers whereas rivers that deposited many of the red bed sequences in the past probably were shorter streams flowing directly from upland areas to continually aggrading lowlands. Uncertainty about the effectiveness of a direct derivation of red pigment from lateritic soils is increased by the familiar observation of a predominance of red and reddish-brown colors and a paucity of yellowish-brown colors in ancient mudstones compared with modern alluvium.

In order to account for these observations, a supplementary process of aging of inherited yellow-brown oxide to hematite has been proposed (Crosby, 1888, 1891; Barrell, 1908, p. 287–293; Krynine, 1950, p. 143–159). According to this proposition, ferric oxides concentrated in deeply weathered soils provide an adequate supply of potential pigment. Rapid deposition in an oxidizing environment preserves the inherited oxides, and with burial and aging yellow-brown oxide is converted to additional hematite. In contrast, mud that receives little free ferric oxide from the source area or is deposited in a reducing environment produces drab sedimentary rocks. As a result most red and yellow-brown sediments are converted either to drab or to red rocks. But the conversion may not be universal or complete, especially in porous sandstones.

Considered in detail, the process probably is not simply weathering at the place of deposition for continued accumulation hinders the development of soil profiles, thus retarding aging and dehydration of hydrous and hydrated ferric oxides. It is possible, of course, that very slow aggradation in warm, humid climate may enable inherited yellow-brown oxides to age to hematite as they accumulate, but as a general process flood-plain weathering probably has not been im-

portant in the origin of red bed pigment. Studies of the ferric oxide minerals and of the iron oxides in soils combine to indicate that the yellow-brown oxide involved in the transformation through aging is not the hydrated oxide, goethite, but is hydrohematite instead (Scheffer, Welte, and Ludwieg, 1957). The possible role of hydrohematite in the formation of red pigment, as outlined here, cannot be evaluated adequately until the distribution and behavior of the mineral have been investigated in detail.

Deep burial and high temperature have been cited as producing red beds through the dehydration of goethite (Blackett, 1956, p. 12). The fact that sediments buried to a depth of 10,000 feet or more may be subjected to critical temperatures of 100–150° C suggests that hematite in some red beds may have been produced by high temperature dehydration of goethite or hydrohematite (see Tunell and Posnjak, 1931, p. 338). Nevertheless, there is no consistent relationship between depth of burial and redness of formations that makes deep burial necessary in the origin of red pigment.

The hematitic pigment in some red beds is a chemical cement apparently derived from alteration of such iron-bearing minerals as magnetite, ilmenite, biotite, pyroxene and amphibole during transportation and deposition (Robb, 1949; Valeton, 1953, p. 359; Creer, Irving, and Runcorn, 1954, p. 9; Blackett, 1956, p. 63). Destruction of the minerals in reducing environments may have been followed by precipitation of the released iron as hematite coatings on sand grains and clay platelets in oxidizing areas where the iron-bearing minerals are preserved unaltered (Miller and Folk, 1955). Blackett (1956, p. 12) and Irving (1959, p. 52) maintain that the magnetization of many red beds lies in hematite produced by chemical changes after deposition. In fact, magnetization of this sort may be acquired long after deposition. For example, Doell (1956) found that a precipitated iron-oxide coating on grains in a Tertiary formation in California is the seat of magnetization acquired after burial and regional folding of the deposit.

Post-depositional precipitation of hematite does not appear to be an adequate general explanation of the origin of red pigment, especially in those thick, impervious red mudstone sequences with rare interbedded drab layers. Nevertheless, some modification of inherited pigmenting material may take place, as in the extensive red beds associated with evaporites. Swineford (1955, p. 154–155) believes that the upper Permian red beds of Kansas are primary detrital deposits but that the uniform orange-red color may be attributed to thorough redistribution of of ferric oxide from complex colloids in contact with highly alkaline sea water. Moreover, redistribution of hematite probably produced a red coating on sand grains in porous eolian sandstone in some red bed sequences (Dunham, 1953; Shotton, 1956). The actual process by which the red coating was deposited after rounding of the grains at the place of deposition is difficult to decipher, however.

Clearly the problems of red bed pigmentation are so manifold that current information and opinions cannot provide a unifying explanation. Although hematite undoubtedly is the most common oxide, others may also be present. Most of the red pigment probably is inherited hematitic clay, yet some of the ferric oxide apparently has been redistributed in colloidal and possibly chemical form after deposition, and some of it may have been altered diagenetically.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 31, NO. 2, PP. 301–320
FIGS. 1–7, JUNE, 1961

SOCIETY RECORDS AND ACTIVITIES

REPORTS AND MINUTES OF THE THIRTY-FIFTH ANNUAL MEETING OF THE SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

The thirty-fifth annual meeting of the Society of Economic Paleontologists and Mineralogists was held in the Denver Hilton Hotel, Denver, Colorado, April 24–27, 1961, in conjunction with the annual meeting of The American Association of Petroleum Geologists.

The Society's program consisted of papers on the record of water movements in the development of recent and ancient sediments; papers on paleontology, stratigraphy, and mineralogy; and a special group of papers on the classification of carbonate rocks.

At a joint session on Tuesday morning, April 25, William M. Furnish, President of the S.E.P.M., presented the following address:

THE ROLE OF A SPECIALIST

Mr. Chairman, fellow members of S.E.P.M and A.A.P.G., and guests, in spite of the title, it is my plan to speak about the Society of Economic Paleontologists and Mineralogists, or rather the personnel of this organization. The name is an unwieldy one (incomprehensible to the non-professional), and has been recommended for change. Nevertheless, it seems to be appropriate. If it is possible to interpret the original aims of the S.E.P.M. in a broad sense, it seems to me that it can be regarded as sponsoring expertness or specialization in one phase of petroleum geology. This group was not exclusive, but most had the same interest.

Just thirty-five years ago the initial step was taken by a group of some fifteen paleontologists attending the American Association of Petroleum Geologists meeting in Dallas. Originally designated or regarded as an affiliate of the Association, this Society was conceived to sponsor publication of papers promoting "the science of stratigraphy" through research on microfaunas, as well as larger fossils, and the use of "mineral grains" for correlation; especially as these studies related to petroleum geology. This original purpose is as appropriate today as it was a third of a century ago, and the Society personnel probably have proportionately the same responsibility. It appears, however, that practices and perspectives have altered the concept greatly during the years.

The identity of the Society at this early stage was almost exclusively with micropaleontology. Henry V. Howe presided at the first meeting in March, 1927, when the constitution was adopted. Joseph A. Cushman was first editor; the second editor, Raymond C. Moore, served for nine years. The initial volume of the *Journal of Paleontology* contained a series of studies on the systematic description of small organisms of potential usefulness in oil field stratigraphy, and the techniques employed in such work; a single paper described a method of assigning sand-grain roundness values. Volume I of the *Journal of Sedimentary Petrology* appeared, in 1931, with Moore as editor. The initial number included studies on shapes of particles, bottom samples, accessory minerals, insoluble residues, and clay mineralogy. Bulman outlined the problems of environmental effects on subsurface stratigraphy, and Milner surveyed Sedimentary Petrology, past and future.

It should be mentioned that twenty to thirty years ago the term "Paleontology" was often used in a broad sense as far as the petroleum industry was concerned. Correlation of formations within the domain of practical oil geologists was accomplished by an expert who used "bug tops" for identity. At least in some areas, such as the Gulf Coast, microfossils were the ultimate basis for recognition of beds as they were drilled. At the time this Society originated, cutting samples were accumulated in a most casual fashion, but a few companies initiated sample "libraries." Spot cores were customarily used for identifying the formations lithologically and faunally. During the thirties there were many individuals assigned to documenting well information by plotted

sample logs. The unofficial title of "paleontologist" was assigned indiscriminately, even though the individual may have been unable to differentiate *Guembelina* from *Textularia*, or had little reason to do so. A few standard markers in the interior basin sediments were established on the upper limits of distinctive carbonate, sandstone, or evaporite units in an otherwise monotonous section. In such a case, fossils had less value for identification than intervals and sequences. From a practical standpoint, the degree of knowledge represented by the expert allowed use of fossils in about the same fashion as petrographic detail. The casual student found "near likenesses" to index species throughout similar lithologies. "Hard rock" paleontologists of the Midcontinent unashamedly identified "brachiopod shells and crinoid fragments" instead of key forms. Of course, there were exceptions to these generalizations.

Another stage in the use of expert knowledge for correlation developed in the thirties with widespread availability of electric logs. For a time, the logging engineers (many with geological training) used sample and core logs to establish an acquaintance with local formations and to present a lithologic interpretation. Some experienced geologists viewed these "pictures" with suspicion or skepticism; direct comparisons were difficult because of poor quality samples and few core logs. On an empirical basis, it was nevertheless soon apparent to all who were willing to study and compare E-logs, that correlations between nearby wells in some formations was so obvious that anyone could accomplish it without tedious preparation. This principle was so well conceived that the role of expert could scarcely be applied; drilling and production personnel were able to identify critical points at a glance. Line-depth measurements were so nearly precise, compared with pipe tallies and samples presumably caught "two-per-joint," that datum points were based upon electric-logs exclusively. "Weevils" were tossed a new pile of logs each morning to mark with formation tops and soon became accomplished "slippers." A geologist with a few months' experience correlating logs, or residence in a development area, could identify standard markers across the room or rig floor. The same practice served equally well in the Ordovician and Eocene, with relatively few complications or mysteries. "Amplified" curves provided distinctive patterns in sections lacking apparent lithologic change. Signature patterns and point-for-point correlations were no longer the prerogative of an expert. Under ideal conditions, local correlation became a dreary task as far as hundreds of development wells were concerned. Few stratigraphic problems were encountered or solved as long as emphasis was placed on recognition of "standard datum points."

Nevertheless, the precise measurements and detailed mechanical correlations made it possible to secure an insight into stratigraphy never before possible. For example, an unconformity involving only a few tens of feet of bevel could be analyzed bed-by-bed in three dimensions. Depositional variations in both interval and lithology could be traced and identified with a high degree of certainty. The geologist was provided a view far more comprehensive than could be attained by surface examination under the best circumstances. Without direct comparison, an experienced geologist had fixed in mind a "standard log" which provided all key stratigraphic determinations from memory, with a good insight of structure and facies as well.

Thus an impersonal monster spelled "finis" for a primary function of the ordinary paleontologist and his low-power binocular.

As the use of electric-logs increased, sample loggers ceased to exist in some organizations. There were still problems to be solved by a study of fossils; important wildcats secured well-site determinations or expert laboratory identities of critical markers. This relationship still exists, to a degree, and will at least until continuous logging becomes standard practice. In the meantime, a capable well-sample logger can now qualify as an expert or specialist, if he is able to make positive stratigraphic identifications beyond structural control and equate the vagaries of drilling operations to precise depth measure.

The field of practical paleontology was stifled but never died. Over a period of years the classic faunas of Cretaceous-Tertiary foraminifera and ostracodes became well

documented. In the Paleozoic, a series of microfaunal groups have come into prominence. The value of fusulines for gross dating and detailed correlation of Pennsylvanian-Permian strata has been demonstrated repeatedly. Conodonts have been found useful, especially in the Devonian. A variety of other groups show promise or can be used in some fashion. The few groups now considered to have little or no correlating value arouse a lingering doubt that further systematic study might prove their usefulness. However, in commercial work there have been many instances of false starts in research assignments which lead to no positive results.

The obstacle of mastering techniques and resolving them to routine is a minor problem compared to familiarization with the complex data. Only a few types of fossils lend themselves to practical paleontology in a fashion whereby anyone but the expert can utilize them effectively. In spite of all the mechanical devices and laboratory aids, direct familiarity through tedious application by a specialist remains a prerequisite. Only such a specialist comprehends the language of description and picture. It takes a "trained eye" to verify that this fossil is really the same as that presented in the literature (more to the point, not the same as that one). Identifications are highly subjective, and the meanings rarely can be simply analyzed. The advantages of a strictly artificial key, set up with reference material alone, seldom prevail over the use of published literature. Published catalogues, range charts, monographs, and treatises have provided great incentive by simplifying this task.

The status of this phase of science as applied to industry or the role played by such a specialist remains one of importance. The optimistic view on the future value of diverse groups outlined by Thalmann at the New York meeting suggests that it is only needed for paleontologists to branch into a variety of fields. Certainly none of the groups has been fully exploited; many have just been discovered. Those best known, the foraminifera, also serve in the best fashion for deciphering paleoecology.

What is the purpose in a study of fossils today? Paleontology as a broad field still has a usefulness in the original sense visualized by the founders of S.E.P.M., but this application is limited compared to the overall growth of the science. The role played by the specialist in this field has become increasingly vital in other respects not so closely allied to "operations." Age determinations and correlation on a regional basis is still a function of faunal determination. Even today, problems are legion. Falsehoods may be perpetrated under the guise of correlation as a result of inadequate knowledge, conflicts of evidence, or subjectivity. In the use of fossils the goal of securing knowledge is always just beyond reach, or subject to additional refinement. Also the shadow of homotaxial relationship is a constant threat to the systematist who carefully lines up stratigraphy with faunal "zones" and "subzones." Perhaps there are cases in which we have exceeded the calibration of our measure (evolutionary development resolved to a study of hard parts), but the history of this science has always been one of taking another closer look. Abandonment of the concept of world-wide synchronous gaps in the record has involved no profound adjustment in paleontology. This field of study will also survive approach to the "new" species concept involving statistical limits, rather than the sanctity of types. Paleontologists will certainly continue to change practices in the future as they have in the past. It appears that the relatively new and scanty absolute dating by geochemistry poses no more of a threat to a study, of, say Paleozoic fossils than it has to archeology, a field enhanced greatly by the new information available. The variety of fields now open for application of faunal studies, such as paleoecology, now has the appearance of being factual, or at least founded on something beyond conjecture. Interpretation of this fund of knowledge to paleoclimatology, by an application of systematic paleontology, or to paleogeography in a strict sense involving changing poles or continental drift is still in an early state. The experience throughout has been that such "academic" information invariably has practical application not recognized in advance. It is fitting that a fair proportion of basic research is now supported by industrial organizations; their staff may

include a good many "oil geologists" who are actually specialists well divorced from oil field operations.

Mineralogy-Petrology, as a field of investigation paralleling that of fossils in correlation, failed to materialize, but does not suffer by comparison as an important field of investigation. Solving regional tectonics by physical measure of sediments alone never approached the role once imagined. At the same time, the use of newer techniques in this regimen has much wider application than could have been visualized thirty-five years ago. There has been so much learned from sources previously unavailable, that today's specialists should be impressed by the complexity and the need for still more basic data. Analysis of quartz detritus, once the main subject of investigation, has been bypassed as "limestone" and "shale" have assumed a spectacular variety of form. These studies have spawned a verbage which must appall the old-time field geologist and well sitter.

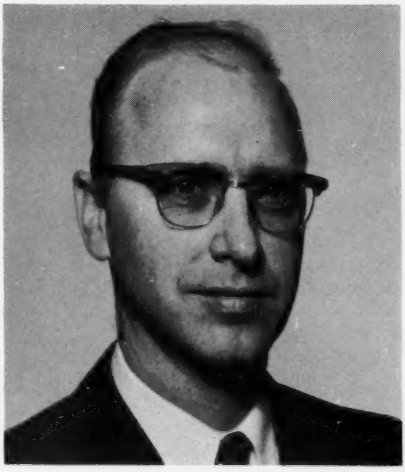
Another matter of concern today is the origin of specialists and future source of these individuals. The problem as to whether paleontologists are to be trained primarily as biologists and mineralogists as chemists has been rather thoroughly explored (as an example, J. B. Knight's address of 1947 and the flurry of subsequent comments). The prejudiced opinion of most teachers and practical geologists in America is that individuals in these fields be qualified in all phases of earth science. Irrespective of the merits of such a procedure, there are some redeeming features: high school training has been accelerated as far as basic science and mathematics is concerned and opportunities for intensive research experience in universities have been aided by fellowship funds. A stated principle for university education is: nothing should be taught which can be learned better on the job in a few months. Certainly, this rule has not been the controlling thought in geologic curricula over a period of years. Potentially, advanced university study provides a sifting process, together with disciplines and associations conducive to accomplishment, an atmosphere favorable for the creation of specialists.

Also at the Tuesday morning joint session, the following awards were made: Best paper in the 1959 *Journal of Paleontology*, Best paper in the 1959 *Journal of Sedimentary Petrology*, Best paper at the 1960 Atlantic City Convention, and Recognition of Correspondents.

The award for the Best Paper in the 1959 *Journal of Paleontology*, consisting of an appropriate scroll, was presented to joint authors—Paul D. Blackmon and Ruth Todd, for their paper entitled, "Mineralogy of Some Foraminifera as Related to Their Classification and Ecology," published in Volume 33, Number 1 (January, 1959).

Paul David Blackmon, now with the U. S. Geological Survey, Branch of Experimental Geochemistry and Mineralogy, Denver, Colorado, was born in Buffalo, New York, on December 11, 1924. After 2½ years in the United States Navy (1944–1946), he attended the University of Buffalo where he received a B.A. degree in February of 1951 and later an M.A. degree from the same institution.

In July of 1952 Mr. Blackmon was employed by the United States Geological Survey where he is at present doing analytical service and research in the field of sedimentary petrology. Mr. Blackmon's



PAUL BLACKMON
Award for Best Paper in 1959
Journal of Paleontology

interests and publications are concentrated on the fields of carbonate geology, clay mineralogy, and glacial geology.

In addition to articles in the *Journal of Paleontology*, Mr. Blackmon has contributed to the *American Journal of Science* and to U. S. Geological Survey publications.

Mr. Blackmon is an associate member of the S.E.P.M., a member of the Geological Society of Washington and the Colorado Scientific Society.

Ruth Todd was born October 22, 1913, in Seattle, Washington. She attended high schools in Seattle and Gering, Nebraska, and received B.S. and M.S. degrees from the University of Washington.

Her entire career, beginning in 1940, has been as a member of the paleontology and stratigraphy branch of the U. S. Geological Survey, during the first 10 years serving as Joseph A. Cushman's assistant at the Cushman Laboratory for Foraminiferal Research in Sharon, Massachusetts, then being transferred to Washington after his death in 1949.

Miss Todd's studies, since 1950, have been on Recent and Tertiary smaller Foraminifera from the Tropical Pacific, especially their ecology and use in correlation. She has published several U. S. Geological Survey Professional Papers and has published, among others, in the *American Journal of Science*, the *Bulletin of American Paleontology*, and the *Journal of Paleontology*.

RUTH TODD

Award for Best Paper in 1959
Journal of Paleontology

Miss Todd is a fellow of the Geological Society of America and the Cushman Foundation. She is a member of the Paleontological Society, The American Association of Petroleum Geologists, the Washington Academy of Science, and Sigma Xi.

R. G. C. BATHURST

Award for Best Paper in 1959
Journal of Sedimentary Petrology

The award for the Best Paper in the 1959 *Journal of Sedimentary Petrology*, also a scroll, was presented to Robin Gilbert Charles Bathurst, for his paper entitled, "Diagenesis in Mississippian Calcilutites and Pseudobreccias," published in Volume 29, Number 3 (September, 1959).

Born on March 21, 1920, in London, England, Mr. Bathurst is now a teacher of sedimentology and stratigraphy at the University of Liverpool. He attended Aldenham School in Hertfordshire and did undergraduate work at Chelsea Polytechnic Institute. He received a B.Sc. degree in geology from the Royal College of Science, London, in 1948, and a M.Sc. from Cambridge University in 1953. Except for war service Mr. Bathurst has been connected with the University of Liverpool since grad-

WAYNE A. PRYOR (left) receiving Award for Best Paper at 1960 Convention.

uation. He spent the spring term of 1960 as a visiting professor at the California Institute of Technology, and most of last summer was spent visiting U. S. oil companies and universities, giving lectures or leading in discussions.

Mr. Bathurst's general field of interest is limestone diagenesis and he has published papers on this subject in the *Journal of Geology* as well as the *Journal of Sedimentary Petrology*.

Mr. Bathurst has been an associate member of the S.E.P.M. since 1951 and is also a member of the Geologists' Association of London and the Liverpool Geological Society. In addition, he is a member of the Geological Society of London.

Dr. Wayne A. Pryor was the recipient of the award for the "Best Paper at the Convention." A book by Philip B. King, *Evolution of North America*, was presented to him, for his paper, "Dispersal Centers of Paleozoic and Later Clastics of the Eastern Interior and Adjacent Areas," which was given at the 34th Annual Meeting of the Society in Atlantic City, New Jersey, in 1960. His paper was judged by a committee of five on content, organization, originality, and presentation.

Now a research geologist with the Gulf Research and Development Company in Pittsburgh, Pennsylvania, Mr. Pryor was born in Bellvue, Pennsylvania, on May 6, 1928. He received a B.S. degree in geology from Centenary College in 1952; an M.S. in 1954 from the University of Illinois, and his Ph.D. from Rutgers in 1959.

Dr. Pryor has worked for several years for the Illinois Geological Survey doing research in ground water geology and since 1959 has been employed by Gulf, his main interest being sedimentation and clastic mineralogy.

Several of Mr. Pryor's articles have been published in the Illinois State Survey Bulletins. He has also published papers on sedimentation in the *Journal of Sedimentary Petrology* and stratigraphic studies in the *A.A.P.G. Bulletin*.

In addition to S.E.P.M. membership. Dr. Pryor is a member of The American Association of Petroleum Geologists and the Geological Society of America.

The Society's Research Committee nominated and the Council elected two Correspondents—Kotora Hatai and A. Eisenack, in recognition of their outstanding contribution to the field of geology. This award consists of a scroll and the receipt of the

KOTORA HATAI

Elected S.E.P.M. Correspondent
June 21, 1960

Journal of Sedimentary Petrology for life.

Kotora Hatai, now a professor at Tohoku University, Institute of Geology and Paleontology, Sendai, Japan, was born in Ridley Park, Pennsylvania, on July 21, 1909. He graduated from the above Institution in 1935 and received a Doctor of Science degree from Tohoku Imperial University in 1948.

Dr. Hatai has devoted his professional efforts to the teaching of geology and has done research in marine and coastal geology and paleontology. His publications deal mostly with the Tertiary period and he has done extensive study on brachiopods, otoliths, molluscs, and cirripeds.

Professor Hatai is a member of the Paleontological Association of Japan, the Oceanographic Research Committee of UNESCO, the Malacological Society of Japan, the Mineralogical Society of Japan, the Biogeographical Society of Japan, and has been an associate member of the S.E.P.M. for 12 years.

Professor A. Eisenack was born May 13, 1891, in Altfelde, East Prussia. He studied at the Universities of Jena and Konigsberg in Prussia, and graduated from the University of Konigsberg in 1931 with a Doctor of Philosophy degree. Since 1951 he has been a professor of geology at the University of Tubingen, Germany.

A. EISENACK

Elected S.E.P.M. Correspondent
June 21, 1960

Dr. Eisenack's main field of interest is micropaleontology, and he has written many scientific articles about graptolites, retiolites, dinoflagellates, and hystrichospheres.

Professor Eisenack is a member of Palaontologischen Gesellschaft and Naturforscher und Arzte.

ANNUAL BUSINESS MEETING

The annual business session of the Society was called to order at 1:30 P.M., Tuesday, April 25, by William M. Furnish, President, who introduced the officers for the new year as follows: President, L. L. Sloss; Vice-President, Kenneth E. Lohman; Secretary-Treasurer, Lloyd C. Pray; Editors of the *Journal of Paleontology*, M. L. Thompson and Charles W. Collinson; Editor of the *Journal of Sedimentary Petrology*, Lewis M. Cline; and Councilors, Lyman D. Toulmin and Albert L. Kidwell.

It was moved, seconded, and carried that the minutes of the 1960 meeting be approved as published in the June, 1960, *Journal of Sedimentary Petrology* and the July, 1960, *Journal of Paleontology*.

The following reports were not presented at the Business Meeting, but instead they are printed in full below.

Report of the Editors of the Journal of Paleontology (M. L. Thompson and Charles Collinson).—Volume 34 (1960) of the *Journal of Paleontology* was published in association with The Paleontological Society and includes, in total, 1228 pages of text and 144 plates, representing 94 papers. The March, July and November issues of the *Journal* were prepared by the Society of Economic Paleontologists and Mineralogists and contain 540 text pages and 64 plates representing increases of 2% and 20%, respectively, over Volume 33. Fourteen of the 64 plates were 300 mesh halftone offset reproductions. The remainder were collotype fulltone reproductions.

Altogether, 39 papers, nine paleontological notes, one nomenclatural note, a review and various Society records and activities were published. Most of the manuscripts originated in midwestern United States with the

S.E.P.M. INCOMING COUNCIL

(For the term ending March, 1962)

Front row, left to right: KENNETH E. LOHMAN, Vice-President; L. L. SLOSS, President.
Second row, left to right: W. M. FURNISH, JR., Past-President; CHARLES W. COLLINSON, Co-Editor of *Journal of Paleontology;* LLOYD C. PRAY, Secretary-Treasurer.
Back row, left to right: LYMAN D. TOULMIN, Councilor (Paleontology); LEWIS M. CLINE, Editor of *Journal of Sedimentary Petrology;* ALBERT L. KIDWELL, Councilor (Mineralogy).
Not shown in picture: M. L. THOMPSON, Co-Editor of *Journal of Paleontology.*

eastern U. S., Gulf Coast, western U. S., and West Coast following in that order. Manuscripts originating in Australia, Germany, India, Mexico, and U.S.S.R. were also published.

On February 1, 1961, the editors had on hand 43 manuscripts accounting for 1886 manuscript pages and 95 plates. These materials represent a backlog of three and a half issues and a publication delay (for manuscripts received after February 1, 1961) of approximately eighteen months. The average delay in publication for Volume 34 was about ten months.

One of the principal activities of the editors during 1960 was the final preparation of the *Genus-Species, Subject-Author Index to Volumes 1–25* of the *Journal of Paleontology.* On February 1, 1961, page proof for the Subject-Author Index had been read and page-proofing of the Genus-Species portion was in progress. The volume should be ready for distribution before midyear 1961.

The editors are grateful to the Illinois State Geological Survey which provided editorial and financial assistance during the past year. Frances Alsterlund and Romayne

TABLE 1.—*Subject Matter of Manuscripts Published by S.E.P.M. in Vol. 34, Journal of Paleontology*

Subject	Number of Manuscripts
Micropaleontology	18
Macropaleontology	13
Cephalopods	5
Brachiopods	4
Bryozoans	4
Conodonts	3
Foraminifera	3
Paleobotany	3
Techniques	3
Gastropods	2
Ostracods	2
Paleoecology	2
Biostratigraphy	1
Blastoids	1
Branchiopods	1
Calcisphaeres	1
Conchostrachans	1
Graptolites	1
Stromaloporoids	1

Ziroli of the Survey Staff deserve special acknowledgment for their efforts in preparing both the *Journal of Paleontology* and the 25 year Index.

The George Banta Company, Inc. likewise deserves special thanks for cooperation and understanding beyond the normal duties of a publisher.

2. *Report of the Editor of the Journal of Sedimentary Petrology* (*Jack L. Hough*).—The *Journal of Sedimentary Petrology* was published in 1960 as Volume 30, Numbers 1 through 4.

The March number was expanded to 192 pages to accommodate a large backlog of manuscripts. The June and September numbers contained 160 pages each. The last number, in December, was restricted to 128 pages in an attempt to stay within the budget. Meanwhile, the supply of manuscripts had continued to increase, and the delay in publication had grown longer. At the close of the year the backlog of manuscripts was at an all-time high, and all papers were facing a wait of over a year before they could be published. The rate of receipt of new manuscripts was accelerating. The *Journal* is faced with the need, either to turn down many desirable contributions or to expand in size. An expansion in size can only be accomplished if dues and subscription rates are again raised, or if some as yet unknown angel will subsidize publication.

A summary of the contents of the *Journal* is given in the accompanying table. A trend toward publication of a larger number of major papers has been continued during 1960, when the average length of articles increased from 9 pages (in 1959) to 12 pages. The editor has received unsolicited expressions of approval of the publication of the longer papers, from several highly-respected members of the Society; it appears, therefore, that a restriction on length of papers would not be a desirable means of providing space for a larger number of papers.

The national origins of the articles, notes, and discussions of Volume 30 were as follows:

United States	43
England	6
Australia	4
Canada	2
New Zealand	1
South Africa	1

Journal of Sedimentary Petrology, Vol. 30, 1960

	Articles		Notes		Discussions		Reviews		S.E.P.M. Data[1] Pages	Advertising[2] Pages	Other[3] Pages	Total Pages
	No.	Pages	No.	Pages	No.	Pages	No.	Pages				
1. (Mar.)	8	153	2	4.5	—	—	4	3.5	23	3	5	192
2. (June)	11	124	2	7	—	—	2	1.5	23	0.5	4	160
3. (Sept.)	13	143	3	5	—	—	1	1	5	1	5	160
4. (Dec.)	11	106	5	7.5	2	2	—	—	—	—	12.5	128
Total	43	526	12	24.0	2	2	7	6	51	4.5	26.5	640

[1] Including membership list (March) and minutes of Annual Meeting (June).
[2] Exclusive of advertisements on covers.
[3] "Other" includes title pages, index, errata, and miscellaneous announcements.

As in the past eleven years, the University of Illinois provided the services of the Editorial staff of the *Journal*. During 1960, Dr. Frederick W. Cropp served as Managing Editor and Mr. Peter Fenner served as editorial assistant.

It was with regret that the Editor withdrew from nomination for re-election to another term of office because of a need to find time for research and other activities. During the twelve years of his service as Editor, the *Journal* has expanded in size from 148 pages to 640 pages per volume (with an increase in number of words per page, meanwhile), and the amount of editorial work involved has increased in proportion.

3. *Report of the Secretary-Treasurer (John Imbrie).*—Income from all sources in 1960, excluding Special Publications, was $8,000 more than in 1959, with an extension in expenses of only $5,000 over 1959. This is due in part to an increase in the subscription rate of the *Journal of Sedimentary Petrology*. The 1960 rate was $11.00 per year, $2.00 over the 1959 rate.

The greatest increase in operating expenses is attributable to printing expenditures, which is more than $3,000 over the 1959 figure. Also included in this amount are increases in salaries, postage, wage taxes, and the expense of the convention. The miscellaneous column in income was augmented with $500 from the Johnson Reprint Corporation for the right to reprint certain volumes of the *Journal of Paleontology;* however, we incurred an additional miscellaneous expense of $345 for attorney fees.

The sale of back numbers increased about $1,000. $700 of this amount represents the sale of two reprinted volumes of the *Journal of Sedimentary Petrology*, which are still in the red about $800.

As of December 31, 1960, our balance in the bank was $45,101.25—an increase over the 1959 figure. The general fund showed a gain of $2,000, but the publication fund showed a drop of $1,000 in round figures. The publication fund is at a dangerously low level. The cost of publishing Barker's *Taxonomic Notes* was $7,450 and has shown a

(*Continued on page 313*)

MEMBERSHIP, MAILING, AND JOURNAL STATISTICS

	Dec. 31, 1960	*Dec. 31, 1959*	*Dec. 31, 1958*
1. S.E.P.M. Membership:			
Active Members	1207	1134	1094
Associates	411	384	351
Correspondents	6	6	6
Honorary Members	7	6	5
	1631	1530	1456
2. *Journal of Paleontology* Mailing List:			
S.E.P.M. Active & Honorary Members	505	509	503
S.E.P.M. Associates	181	173	167
Subscribers	1014	962	912
P.S. Members	741	699	649
	2441	2343	2231
3. *Journal of Sedimentary Petrology* Mailing List:			
S.E.P.M. Active & Honorary Members	836	775	726
S.E.P.M. Associates	277	261	220
S.E.P.M. Correspondents	6	6	6
S.E.P.M. Subscribers	1159	1076	997
	2278	2118	1949
4. Edition of *Journal of Paleontology*	2600	2500	2500
5. Edition of *Journal of Sedimentary Petrology*	2700	2600	2500
6. Number of pages, *Journal of Paleontology*	1228	1139	1170
7. Number of pages, *Jour. Sed. Petrology*	640	632	528
8. Number of plates, *Journal of Paleontology*	144	133	148
9. New members	169	153	125
10. Transfers to active membership	35	32	24
11. Members and associates dropped for non-payment of dues 1/1/61	66	43	65

REPORT OF CERTIFIED PUBLIC ACCOUNTANTS

The Council,
Society of Economic Paleontologists
and Mineralogists:

We have examined the accompanying balance sheet of the Society of Economic Paleontologists and Mineralogists at December 31, 1960, and the related statement of income and surplus for the year then ended. Our examination was made in accordance with generally accepted auditing standards, and accordingly included such tests of the accounting records and such other auditing procedures as we considered necessary in the circumstances.

In our opinion, the statements mentioned above present fairly the financial position of the Society of Economic Paleontologists and Mineralogists at December 31, 1960, and the results of its operations for the year then ended, in conformity with generally accepted accounting principles applied on a basis consistent with that of the preceding year.

ARTHUR YOUNG & COMPANY

Tulsa, Oklahoma
January 14, 1961

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS
BALANCE SHEET, DECEMBER 31, 1960

ASSETS

	Total	*General Fund*	*Publication Fund*
CURRENT ASSETS:			
Cash	$41,062.71	$32,798.82	$ 8,263.89
Savings account	4,038.56	4,038.56	—
Accounts receivable	391.57	315.57	76.00
Total current assets	45,492.84	37,152.95	8,339.89
PUBLICATIONS:			
Journal of Paleontology:			
Issues prior to 1960—9,742 journals at $0.50 each (1,488 complete volumes)	4,871.00	4,871.00	—
Issues 1 to 6 of 1960—876 journals, at cost	1,793.15	1,793.15	—
Reprints in 1948, Volume 1, 1927—615 volumes, at cost	1,335.57	1,335.57	—
Journal of Sedimentary Petrology:			
Issues prior to 1960—6,628 journals at $0.50 each (1,734 complete volumes)	3,314.00	3,314.00	—
Issues 1 to 4 of 1960—1,207 journals, at cost	1,613.07	1,613.07	—
Reprints in 1960, Volume 19, 1949—341 volumes, at cost	494.96	494.96	—
Reprints in 1960, Volume 21, 1951—353 volumes, at cost	834.09	834.09	—
Special publications, at cost:			
Turbidity Currents, 14 copies	11.97	—	11.97
Recent Marine Sediments, 92 copies	189.84	—	189.84
Finding Ancient Shorelines, 13 copies	22.72	—	22.72
Regional Aspects of Carbonate Deposition, 10 copies	22.32	—	22.32
Journal of Sedimentary Petrology Index, 1,216 copies	702.00	—	702.00
Silica in Sediments, 774 copies	1,708.99	—	1,708.99
Taxonomic Notes—Brady Foraminifera—Challenger Expedition:			
Bound—791 copies	2,967.36	—	2,967.36
Unbound—1,100 copies	3,691.80	—	3,691.80
Total publications	23,572.84	14,255.84	9,317.00
FURNITURE AND FIXTURES (less reserve, $1,857.34)	1.00	1.00	—
DEFERRED CHARGES	5,020.64	794.39	4,226.25
	$74,087.32	$52,204.18	$21,883.14

LIABILITIES AND SURPLUS

CURRENT LIABILITIES:			
Accounts payable	$ 7,622.44	$ 3,716.05	$ 3,906.39
Amount payable to Paleontological Society	3,547.69	3,547.69	—
Total current liabilities	11,170.13	7,263.74	3,906.39
DEFERRED CREDITS:			
Subscriptions to journals—net of portion to be received by Paleontological Society	12,013.41	12,013.41	—
Membership dues for 1961	10,076.00	10,076.00	—
Advance sales, Journal of Paleontology Comprehensive Index	2,103.20	—	2,103.20
Total deferred credits	24,192.61	22,089.41	2,103.20
SURPLUS	38,724.58	22,851.03	15,873.55
	$74,087.32	$52,204.18	$21,883.14

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS
STATEMENT OF INCOME AND SURPLUS
YEAR ENDED DECEMBER 31, 1960

	Total	*General Fund*	*Publication Fund*
INCOME:			
Membership dues and subscriptions:			
Journals of Paleontology and Sedimentary Petrology	$ 4,913.00	$ 4,913.00	$ —
Journal of Paleontology	18,222.10	18,222.10	—
Journal of Sedimentary Petrology	17,722.10	17,722.10	—
	40,857.20	40,857.20	—
Sales of special publications:			
Turbidity Currents	43.75	—	43.75
Recent Marine Sediments	717.50	—	717.50
Finding Ancient Shorelines	23.00	—	23.00
Regional Aspects of Carbonate Deposition	294.00	—	294.00
Journal of Sedimentary Petrology Index	137.00	—	137.00
Silica in Sediments	1,012.75	—	1,012.75
Taxonomic Notes—Brady Foraminifera—Challenger Expedition	1,890.15	—	1,890.15
	4,118.15	—	4,118.15
Sales of back numbers:			
Journal of Paleontology	4,809.45	4,809.45	—
Journal of Sedimentary Petrology	2,588.05	2,588.05	—
	7,397.50	7,397.50	—
Sales of plates	528.79	528.79	—
Advertising	539.56	539.56	—
Donation from The American Association of Petroleum Geologists	2,040.00	2,040.00	—
Miscellaneous	917.66	917.66	—
	56,398.86	52,280.71	4,118.15
Less portion of 1960 income accrued to Paleontological Society	3,811.13	3,811.13	—
	52,587.73	48,469.58	4,118.15
COSTS AND EXPENSES:			
Cost of printing:			
Journal of Paleontology	14,586.00	14,586.00	—
Journal of Sedimentary Petrology	13,503.58	13,503.58	—
Journal of Paleontology—Bound Volume 19	609.31	609.31	—
Journal of Paleontology—Bound Volume 21	993.26	993.26	—
Taxonomic Notes—Brady Foraminifera—Challenger Expedition	7,540.72	—	7,540.72
	37,232.87	29,692.15	7,540.72
Expenses:			
Clerical salaries	8,655.00	8,655.00	—
Office supplies	561.75	561.75	—
Postage and express	2,040.27	2,031.10	9.17
Office rent	2,000.00	2,000.00	—
Telephone	53.56	53.56	—
Audit fee	411.73	411.73	—
Payroll taxes	240.12	240.12	—
Miscellaneous	3,274.95	2,946.36	328.59
	17,237.38	16,899.62	337.76
Adjustment for (increase) in inventory of publications	(7,401.48)	(1,797.26)	(5,604.22)
	47,068.77	44,794.51	2,274.26
NET INCOME	5,518.96	3,675.07	1,843.89
SURPLUS AT DECEMBER 31, 1959	33,205.62	19,175.96	14,029.66
SURPLUS AT DECEMBER 31, 1960	$38,724.58	$22,851.03	$15,873.55

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS
NOTE TO FINANCIAL STATEMENTS

It is the opinion of counsel that the Society, as a division of The American Association of Petroleum Geologists, is exempt from federal income tax under provisions of Section 501(c) of the Internal Revenue Code, except to the extent of "unrelated business income." The Society, based on the opinion of counsel, has taken the position that none of its income is "unrelated business income" within the provisions of Section 512 of the Internal Revenue Code and therefore no liability has been provided for federal and state income taxes in the financial statements.

(*Continued from page 310*)

return of only $1,890. We must expand the sales of the Barker book and *Journal of Paleontology Index* in order to save the publication fund. During 1960 only 200 copies of *Taxonomic Notes* and not quite 300 copies of the *Index* were sold. Other Special Publications showed a profit with the exception of the *Journal of Sedimentary Petrology Index*, but this red figure is now only a little less than $50.00.

Membership shows an over-all enlargement of 101. This compares with a similar figure of 74 for 1959 and 43 for 1958. As of January 1, 1961, 66 members and associates were dropped for non-payment of dues. On January 1, 1960, only 43 were dropped.

Ten members and associates passed away during 1960.

Calder T. Bressler
Julia Gardner
Paul Herbert, Jr.
J. Brookes Knight
John T. Lonsdale
Hubert Schenck
Clinton R. Stauffer
Emmett P. Tatum
Charles W. Tomlinson
H. J. Weeks

The *Journal of Paleontology* mailing list was expanded by 98, and the *Journal of Sedimentary Petrology* mailing list was enlarged by 160. The preceding year showed corresponding figures of 112 and 169 respectively.

4. *Report of the Research Committee* (*Robert N. Ginsburg, Chairman*).—Membership of this Committee is:

1961	*1962*	*1963*
Heinz A. Lowenstam	R. N. Ginsburg	F. Beales
Franklyn B. Van Houten	H. N. Frenzel	A. T. Cross
A. H. Akers	M. L. Natland	D. J. McLaren
A. C. Munyan	R. W. Schweers	J. M. Schopf
P. W. Reinhart	E. J. Guzman	B. H. Burma

At its meeting in 1959 the committee selected Oceanography as the general topic for the annual symposium in 1961.

The chairman chose to consider for the symposium the record of water movements in the development of Recent and ancient sediments. A two-session program was organized by inviting five major papers.

(1) Sedimentation in Tidal Flat Areas of The Netherlands—L.M.J.U. van Straaten
(2) Genesis of Shoreline Sand Accumulations, Northern Gulf of Mexico—H. A. Bernard, C. F. Major and B. S. Parrott
(3) The Effects of Wind-Driven Water Movement on Sediment Distribution, Gulf of Batabano, Cuba—Albert L. Kidwell
(4) Relations of Reefs to Water Circulation —Joshua I. Tracey, Jr.
(5a) Salinity of Florida Bay—John S. McCallum, Kenneth W. Stockman
(5b) Molluscan Distribution in Florida Bay—W. J. Turney
(5c) Variation in the O^{18}/O^{16} Ratios of Florida Bay Mollusks and their Application to Paleogeographic Studies—R. Michael Lloyd

These authors prepared expanded and illustrated summaries that were circulated to some 100 members of the Society. Several "discussers" were invited to comment briefly on each of the papers.

At the annual meeting in Atlantic City, 1960, the committee selected Pollen as the topic for the annual symposium in 1962. Dr. Aureal Cross was named chairman for 1962.

The committee nominated as correspondents, A. Eisenack and Kotora Hatai. These nominations were approved by the Council.

The chairman attempted to simplify the task of selecting the best papers in the Society's *Journals* by pre-selecting six or more papers. Each of the committee members was asked to choose from this selection, or from the *Journals* themselves, the best papers in each *Journal*. The chairman planned to submit each of the three papers in both *journals* that received the most votes to selected specialists for further evaluation. Many of the committee members ranked their three choices, and when these votes were tabulated, the paper entitled, "Mineralogy of some Foraminifera as Related to their Classification and Ecology," by Paul D. Blackmon and Ruth Todd in the *Journal of Paleontology* received the most votes. The committee's vote for the best paper in the *Journal of Sedimentary Petrology* was inde-

cisive. The two papers that received the most votes were submitted to three non-committee specialists who were unanimously in favor of the paper entitled, "Diagenesis in Mississippian Calcilutites and Pseudobreccias," by R. G. C. Bathurst.

5. *Report of the Publications Committee (J. L. Wilson, Chairman).*—The Publications Committee of the S.E.P.M. is composed of J. L. Wilson, Chairman, H. A. Ireland, W. Frank Scott, and Weldon W. Rau; Dr. R. N. Ginsburg, as chairman of the Society's Research Committee, is an ex-officio member for 1960–61. Terms of the first two named members expire April, 1961, and terms of Drs. Scott and Rau continue into 1962.

The principal action taken by the Committee was to recommend to A. C. Munyan, last year's Chairman of the Society's Research Committee, that the S.E.P.M. publish as a special volume its 1960 symposium entitled, "Paleontological and Mineralogical Aspects of Polar Wandering and Continental Drift." The symposium in Atlantic City was well attended and elicited very considerable discussion. It was felt that publication of all of the papers on this admittedly controversial and speculative subject would lead to continued discussion in the interest of science.

The committee has also compiled a short list of Russian paleontological papers to recommend to A.G.I. for translation into English.

At the Committee Meeting in Denver, April, 1961, discussion will take place on the advisability of requesting reviewers for *Journal of Paleontology* articles and on the problem of dealing with the large backlog of manuscripts awaiting publication in the *Journals*.

6. *Report on the Earth Sciences Division of the National Research Council (John C. Frye, S.E.P.M. Representative).*—In accordance with its primary responsibility, the Division during the year rendered advisory services to federal agencies through 12 advisory committees; three fellowship committees and four technical committees also were functioning. Two of the advisory committees, the Committee on Seismological Stations and the U. S. National Committee of the International Association for Quaternary Research (INQUA), were formed during the year. A total of 189 scientists took part in the activities of these several committees.

The new Committee on Seismological Stations, chaired by Professor J. T. Wilson, was appointed at the request of the Department of Defense. Its purpose is to encourage fundamental research in seismology, to provide specifications for a network of standardized seismographs, and to suggest criteria for the selection of the recipient stations. As a result of the committee's first meeting, held in San Francisco in April, 1960, a report on the specifications for a world-wide network of seismographs was published.

The other new committee, dealing with Quaternary research, was appointed at the end of June, 1960, under the chairmanship of Dr. G. M. Richmond. The committee is directed to: (1) organize a U. S. delegation to the 1961 INQUA meeting in Poland; (2) determine whether or not there is enough scientific and financial support to extend, during the 1961 meetings, an invitation to hold the 1965 INQUA meetings in the United States; and (3) bring western hemisphere data and viewpoints more forcefully to the attention of European scientists. The first meeting of the committee was held in conjunction with the G.S.A. meeting in Denver in November, 1960.

The other committees of the Division of particular interest to our society include those on Atomic Waste Disposal, Oceanography, Foreign Field Research Program, Fellowships, Clay Minerals, the National Atlas, and AMSOC.

The Committee on Atomic Waste Disposal on land, on which your representative is also serving as a member, held special meetings at the A.E.C. installations at Hanford, Washington, and the National Reactor Testing Station near Idaho Falls, Idaho. Earlier in the year the committee also visited the A.E.C. sponsored experimental work being conducted in a Kansas salt mine. Research on methods of disposing of radioactive wastes in natural salt beds was first recommended by this committee in 1955. Committee discussions resulting from these three meetings during 1960 were communicated to representatives of the

Commission's Division of Reactor Development.

The Committee on Oceanography is advisory to the A.E.C., C. and G.S., Bureau of Commercial Fisheries, N.S.F., and O.N.R. During the year a number of panels and working groups were active, several conferences were held, and four additional parts of the 12-chapter report, "Oceanography, 1960–1970," were published.

The Foreign Field Research Program Screening Committee during the year selected eight persons from 33 applicants representing 21 institutions of higher learning. The committee on postdoctoral fellowships participates in the screening of applicants in the Fellowship Office of the Academy-Research Council. The number of applicants was about the same as last year and it might be suggested that there should be more competition for these appointments in the Earth Sciences.

The Committee on Clay Minerals held its eighth national conference at the University of Oklahoma, October 12–14, 1959, and its ninth national conference at Purdue University on October 6–8, 1960. An annual volume of papers was prepared as a result of each of these conferences.

The Committee on a National Atlas of the United States has realized that work on the atlas sheets by agencies of the government is proceeding at too slow a rate, and, in order to remedy this, has recommended that the U. S. Geological Survey undertake primary responsibility for the atlas. Atlas sheets currently in print can be obtained from the Superintendent of Documents, Government Printing Office, Washington, D. C., following a recommendation of this committee.

The AMSOC (American Miscellaneous Society Committee) is concerned with planning the ultimate drilling of a hole to the Mohorovicic discontinuity. A preliminary drilling program has been planned and two reports have been issued, "Drilling Thru the Earth's Crust," in 1959, and "Experimental Drilling in Deep Water," in February, 1960. The preliminary drilling program, in addition to furnishing necessary technical and engineering data, is expected to determine whether the second layer of the oceanic crust is sedimentary or igneous.

The annual meeting of the Division was held at the Academy-Research Council Building in Washington, D. C., March 25, 1960, and was attended by the S.E.P.M. representative.

7. *Report of the Joint Committee on Invertebrate Paleontology* (*Raymond C. Moore*). —The most recently completed volume of the *Treatise on Invertebrate Paleontology* series is Part Q on Ostracoda. Copy for pages and illustrations has been delivered to the Meriden Gravure Company in Connecticut for printing. It is anticipated that announcement of availability of bound copies will be mailed from the Geological Society of America headquarters during the spring. This unit contains 442 pages, and thus is comparable to larger previously published volumes. It represents the collaborative work done by 17 authors, and a supplement contains a summary of the recently published USSR volume on this group of fossils.

The next volume to be made ready for Press is Part W which contains sections on conodonts, Problematica, and worms. Typescript and illustrations for this unit have been received and are being processed editorially with expectation of beginning press work in March, 1961.

Other volumes of the *Treatise* nearing readiness for publication are concerned with Foraminifera—at long last being in sight of completion by contributing authors—and the first of three volumes allocated to the Echinodermata. This echinoderm unit will contain general description of the phylum together with morphology and systematic descriptions of primitive pelmatozoans (chiefly cystoids, blastoids, carpoids, edrioasteroids).

Work on yet unfinished volumes is proceeding actively.

8. *Report of SEPM representative on Council of the A.A.A.S.* (*Lloyd G. Henbest*). —Your representative attended the Council meeting of the AAAS December 30 and that of Section E (Geology and Geography). He also attended various scientific sessions. The programs of Sections related to geology treated a number of subjects of interest in petroleum geology and paleontology.

The program of Section E was particularly interesting and well attended. Section E held several joint sessions variously with the

Geological Society of America, Botanical Society of America, Ecological Society of America, American Geophysical Union, and Association of American Geographers. Symposia were held on (a) Palynology; (b) Frontiers in the earth sciences, parts 1 and 2; (c) The Mohole; (d) Selenology; (e) Late Pleistocene of South America; (f) Soviet geography; (g) Economic development and investment in South Africa, and (h) Programming use of natural resources.

Though geologists were prominent among the leaders in organizing the AAAS, they are now so well served by their own national and local societies that Section E has received relatively scant attention from our profession. Under the leadership of Vice-President and Chairman William C. Krumbein, Secretary Frank C. Whitmore, and Program Chairman A. John Haworth, and Past Vice-President Howard A. Myerhoff, Section E has shown new life. Judging by the plans discussed at the Section E committee meeting, December 30, the AAAS meeting in Denver, in December, 1961, will have a program of much interest to SEPM members.

It is recommended that those members of the SEPM who do not belong to the AAAS or subscribe to *Science* take a new look. Since merging with *Scientific Monthly* and undergoing editorial reorganization, *Science* has improved in every respect. Besides having a broadened scientific coverage, *Science* now gives competent attention to national events, issues, and publications that concern scientists. It is also recommended that the SEPM cooperate with the AAAS in every way possible not only for the sake of interdisciplinary exchanges of ideas but in the interest both of improving communication and understanding on all sides of issues affecting scientists and the citizen.

Your representative gained an idea from discussion at the AAAS Council meeting that is recommended for consideration by the members and officers of the SEPM. The increased and improved coverage of scientific events in the newspapers and magazines and response by the public to the AAAS program in New York suggests that the SEPM should consider offering a public lecture as a part of its annual program and as a courtesy to the host town. Communication and publicity in such situations are commonly complicated or inadequate as was shown at New York by the fact that numerous students and adults went to the trouble to inquire how one could attend lectures which were actually programmed for the public. The inquiries indicated (a) increasing public interest in scientific affairs and (b) inadequate publicity. The SEPM membership contains accomplished lecturers and has access to interesting non-member lecturers and programs. It is suggested that communication and publicity might best be obtained by planning well in advance with the local superintendent of schools or principal of the local high school, who would make it an event of the year in high school student and parent activities. It is unnecessary to argue the point that a successful contribution of that kind serves a civic obligation as well as to improve the cultural climate that supports our scientific profession.

9. *Report of Representative on Board of Directors of A.G.I.* (*Samuel P. Ellison*).—Both April and October meetings in 1960 of the A.G.I. Board of Directors were mainly given to a consideration of the reorganization report submitted by the special committee set up for this purpose. After considerable referral back to member societies, a revised version of a new constitution was submitted at the October meeting. The new purposes of the A.G.I. will be to coordinate the activities of its member societies and members. It will promote the advancement of geosciences in the broadest sense, promote fundamental and applied research, promote the improvement of qualifications and attainments of its scientist members, promote high standards in education, professional ethics, and professional performance.

The greatest problem in reorganization is the problem of sustained plans of financing the A.G.I. Solution of this has not yet been resolved.

Throughout the deliberations the S.E.P.M. delegates joined with A.A.P.G. delegates in approval and disapproval of individual items. S.E.P.M. delegates maintained a position that A.G.I. was necessary to the development of the geological profession.

10. *Report of the Permian Basin Section* (*Garner Wilde*).—The sixth annual meeting

of the section will be held April 13–15, 1961, at Midland, Texas. Registration is scheduled to begin the afternoon of April 13th at meeting headquarters, the Scharbauer Hotel. Theme of the technical program is "Sedimentation," and a very fine seminar has been arranged. Mr. Bernold M. Hanson is general chairman.

A field conference which had been held in conjunction with the fifth annual meeting in April, 1960, was offered again in conjunction with the annual meeting of the Southwestern Federation of Geological Societies, October 15, 1960. The field conference, under the very capable leadership of Dr. L. F. Brown, consisted of a detailed inspection of late Virgilian Pennsylvanian rocks of the Brazos River Valley of North Central Texas.

Proposals for joint annual meetings between our section and the Southwestern Federation of Geological Societies have been extended in the hope that conformity to other regional meetings might be achieved. The Permian Basin Section feels, however, that its identity as a regional section must be maintained under such an arrangement.

Officers elected for the 1960-1961 term were: Garner L. Wilde, President; Bernold M. Hanson, 1st Vice-President; Gregory L. Turner, 2nd Vice-President; Cyril J. Perusek, Secretary; Richard D. Jons, Treasurer. Carl Ulvog is immediate past-president. New officers for the 1961–1962 term will be announced at the annual meeting in April.

A series of "Little Lectures" was begun in the Summer in Midland. John Emery Adams spoke on "Ancient Drainage Lines in West Texas," August 29th. Glen L. Evans spoke on "Tertiary Vertebrate Stratigraphy and Paleontology of West Texas," December 6th. A great deal of interest was shown in these very unique lectures, and it is hoped that they might be continued on a year-to-year basis.

As the result of a membership drive held during 1960, the Permian Basin Section has maintained a very substantial membership. Dues notices were recently mailed to over 300 persons, a number of whom reside outside the Permian Basin area.

11. *Report of the Gulf Coast Section* (*Claude M. Quigley*).—During the past year the membership in this section has grown to 323 members. Already this year we have had several new members and we expect to stay as active as we were under the leadership of President David E. Pope during the last year.

October of 1960 marked the completion of the seventh year of the existence of the Gulf Coast Section of the SEPM. As in previous years, our annual meeting was held in conjunction with the Gulf Coast Association of Geological Societies. This has been a very convenient arrangement for our section. Several of our members have published papers in the "Transactions of the GCAGS."

Two publications were compiled during the past year. One is a directory of the Gulf Coast Micropaleontologists, and the other is the initial set of the type locality descriptions. The purpose of this latter publication is to review and describe all Gulf Coast Cenozoic and Mesozoic type localities and, where necessary, designate and describe alternate or reference localities. This first unit, consisting of 53 pages covering 19 stratigraphic units, was published just before the 1960 annual meeting in Biloxi, Mississippi. This project has been financed by a loan from the GCAGS and it is expected that money received from sales will be used to finance the additional units until the area has been covered.

A field trip is scheduled for May 13, 1961, under the direction of Dick Zingula of Humble Oil and Refining Company.

There is a tentative field trip planned in the spring of 1962 to the Tertiary type localities in southwestern Alabama.

In addition to the annual meeting of the GCS-SEPM, there have been local informal meetings of our members in New Orleans and Houston to promote paleontological and mineralogical ideas in these areas. The officers elected for the 1960–1961 term are: Claude M. Quigley, Jr., President; Harold V. Anderson, Vice President; E. Ann Butler, Secretary; and Edward Marks, Treasurer. Mrs. Sybil Lightfoot has been appointed editor of the GCS-SEPM and will handle the papers submitted to her by our members for publication in this year's "Transactions" of the GCAGS.

12. *Report of Pacific Coast Section* (*Edwin H. Stinemeyer*).—The Pacific Section has a paid-up membership of 91 as of January 26th. Delinquent notices have been

mailed out to the remaining 92 active members. As of this date, there is $1963.85 in the treasury. The President is Edwin H. Stinemeyer and Secretary-Treasurer is William J. Lewis.

In 1960, National and Pacific Section S.E.P.M. membership awards and subscriptions to both journals were granted to 24 outstanding students from various Pacific Coast colleges and universities. The faculty of the department of geology or paleontology of each school nominated the student to receive the award. A $25.00 certificate for the best paper presented at the November, 1960, Pacific Section meeting was awarded to Dale Wiggins. The certificate was for the purchase of paleontological publications of the winner's choice. The award paper was, "A Mississippian Microspore Assemblage From White Pine County, Nevada."

The monthly Biostratigraphic Seminar sponsored jointly by the Pacific Section of the S.E.P.M. and Bakersfield College is in progress for the seventh year. Eight papers, by distinguished research workers from the West Coast, covering the fields of stratigraphy, paleontology, sedimentation, ecology and oceanography, are being presented. Mr. William R. Barlow is the Chairman. The average attendance at the meeting is approximately fifty.

The S.E.P.M., this year, will sponsor a spring field trip on May 13th. The trip is being planned and will be conducted by a joint committee from the S.E.P.M. and the San Joaquin Geological Society. We are collaborating on this trip because the Geological Society had selected the same general area and time for their trip. After the initial plans were made, the Pacific Section of the A.A.P.G. wished to hold a day of joint technical papers with contributors from the A.A.P.G., S.E.P.M., and S.E.G.; this session would be held on Friday, May 12th. The decision to have this meeting in conjunction with the field trip was brought about as a result of the Pacific Section A.A.P.G.'s election to move the time of the annual joint convention with S.E.P.M. and S.E.G. from the fall to the spring. The purpose of the move was to avoid conflicts with the G.S.A. meetings. It was further decided that on years when the joint national convention was to be held on the Pacific Coast, that no Pacific Section Convention would be held, but that the Pacific Section's efforts would go to assisting the national convention. To keep geologic interest up, however, a field trip would be held during these years. It was felt that the change to a full fledged convention this year was not practical because of the shortening of the preparation time by six months. As General Chairman for the field trip, I have now also assumed the responsibility for the one day joint technical meeting.

The field trip will be on the structure, stratigraphy and paleontology of the southern border of the San Joaquin Valley. The field trip Chairman is Richard Pierce. A Friday evening dinner meeting will be held to present the general geological framework and some of the stratigraphy that will be viewed on the trip. Thomas W. Dibblee, Jr., of the U.S.G.S. at Menlo Park, California, will be one of the principal speakers and field trip leaders. Mr. Robert Nesbit of the A.A.P.G. will be direct Chairman for the Friday, May 12th meeting.

13. *S.E.P.M. President's Report* (*William M. Furnish*).—The Secretary-Treasurer's report and C.P.A. statement indicate that finances of the Society are in relatively satisfactory condition. As previously anticipated, costs relating to the publishing of the *Journal of Sedimentary Petrology* and *Journal of Paleontology* have increased so substantially as to absorb most of the additional income from new members and higher dues. The sale of back numbers and special publications, which has ordinarily contributed a major part of funds available, are well in arrears for 1960. For example, sales of the comprehensive indices for the two *Journals* have not yet balanced printing costs, although that for the *Journal of Sedimentary Petrology* published three years ago is about even, and that for the *Journal of Paleontology* issued only a month ago will likely be in future demand.

Growth of the Society membership has been increasing normally, but greater additions are needed to solve the problem of publication costs. *Journal* editions are still uneconomically low. The near balance

which had been maintained with the Paleontological Society's subscription to the *Journal of Paleontology* has been upset by a nearly one-fourth increase in that organization's membership. Interest in new S.E.P.M. subscribers continues to favor the *Journal of Sedimentary Petrology*, which has enlarged its coverage greatly and now distributes nearly 2200 copies.

Both of the Society's *Journals* report an increase in the backlog of manuscripts; publication is now delayed longer than a year from receipt. Such a trend justifies an increase in number of pages printed, if their status as leading outlets is to be maintained. No provision has been made for additions in this year's budget, and expenses for the first quarter are under those of a year ago.

Regretfully, Jack L. Hough found it necessary to withdraw from nomination as Editor of the *Journal of Sedimentary Petrology* after serving over ten years in this capacity. Special recognition of his outstanding contribution is acknowledged.

The Research Committee, under Chairman Robert N. Ginsburg, has prepared a symposium for the Denver meetings on the general subject of oceanography. A series of papers dealing with water movement in the development of Recent and ancient sediments is headed by principal guest speaker, L. M. J. U. van Straaten. Next year's plan or a palynology symposium has been complicated by an international conference on this subject at about the same time. Aureal T. Cross, Chairman, will present possible alternatives. Arrangements for publication of last year's symposium on aspects of polar wandering and continental drift are proceeding under the direction of Arthur C. Munyan.

The Permian Basin Section, Pacific Section, and Gulf Coast Section have maintained active programs. Combined memberships now total nearly three-fourths that of active members in the parent Society and Sectional contributions have continued to become of greater importance. Each Section sponsors yearly regional sessions and field conferences. In addition, publications, as well as seminars and lectures or informal meetings, have stressed problems of local interest. It is anticipated that a considerable portion of the responsibility for national meetings will fall on Sections in 1962 and 1963; San Francisco and Houston are host cities.

A Society membership referendum approved support of the American Geological Institute, in principle. Part of the scheduled increase in dues will care for this possible expenditure. In the meantime, reorganization of A.G.I. is pending.

As previously, reports outlining various activities by different committee representatives of the Society will be published in our *Journals*. I hereby express my gratitude to the members who have served as officers, editors, representatives, committeemen and chairmen during the past year. Also, much of the responsibility for providing continuity in Society affairs has rested with the Headquarters' staff. Their capable handling of these details is gratefully acknowledged.

After the President's Report, the following change in the By-Laws, Article I, Section 2, was presented to the Business Meeting for vote by Secretary-Treasurer Imbrie:

"The annual dues of members and associates of the Society who desire only the *Journal of Paleontology* shall be twelve dollars ($12.00). The annual dues of members and associates who desire only the *Journal of Sedimentary Petrology* shall be nine dollars ($9.00). Members and associates may receive both *Journals* by the payment of twenty dollars ($20.00). . . . "

It was moved, seconded, and carried that the dues be increased as proposed.

The meeting was turned over to the incoming president, L. L. Sloss, who called on John C. Osmond to present the *Resolutions of Thanks*.

"The Resolutions Committee, composed of John C. Osmond (chairman), Willard D. Pye, and Thomas W. Amsden, presents the following 'Resolutions of Thanks.'

BE IT RESOLVED THAT in behalf of the Society, we extend an expression of our sincere thanks to the following:

TO LAURENCE L. SLOSS, the technical program chairman, and his very able associates, THEODORE R. WALKER and JOHN CHRONIC, for the preparation and handling of the technical program;

TO R. DANA RUSSELL, S.E.P.M. vice-chairman, for his capable management of the many details involved in planning an annual convention;

TO ROBERT N. GINSBURG, chairman of the Research Committee, for securing and preparing the Research Symposium on 'Water Movements and Sedimentation';

TO WILLIAM E. HAM, for assembling a group of papers on 'Classification of Carbonate Rocks';

TO LAURENCE BRUNDALL, general chairman, HENRY H. R. SHARKEY, general vice-chairman, ORLO E. CHILDS, A.A.P.G. technical program chairman, and to the chairmen and members of all convention committees for their efforts in behalf of the Convention;

TO RUTH TENER, for providing procedural and communication continuity for an organization with annually changing administrations;

TO THE EXECUTIVE COMMITTEE of the A.A.P.G. for so generously appropriating $2,000 as office rent for the Society Headquarters at Tulsa;

TO OUR EDITORS, M. L. THOMPSON, CHARLES W. COLLINSON, and JACK L. HOUGH, for maintaining the quality of our *Journals* on a very limited budget;

TO ROBERT H. DOTT, for serving so ably as Business Manager of the Society."

It was moved, seconded, and carried that the above Resolutions be adopted.

It was moved, seconded, and carried that the following Citation, prepared by M. L. Thompson and presented by Charles W. Collinson, be published in both of our *Journals* as part of the official proceedings:

"After 12 years of loyal and distinguished service to the Society, Jack L. Hough has asked to be relieved of his duties as Editor of the *Journal of Sedimentary Petrology*. Only those who have worked at editorial chores can comprehend the magnitude of Dr. Hough's contribution. Thousands of hours of labor are involved as well as serious responsibilities to individual authors, the Society, and the profession in general.

The years of Dr. Hough's tenure have been highly successful ones. For example, when the Society membership was doubling, the *Journal* quadrupled in size and at the same time grew in quality and scope. Today it is the leader in its field, and the Society is justifiably proud. Such status has resulted from the dedicated efforts of its Editor.

It is indeed a pleasure for the Society to publicly acknowledge our indebtedness to Dr. Hough and to express our sincerest appreciation for his long and distinguished service to the Society."

It was moved, seconded, and carried that the meeting be adjourned.

NEW OFFICERS, PERMIAN BASIN SECTION

The Permian Basin Section of the S.E.P.M. has elected new officers, their one-year term beginning April, 1961. They are as follows:

President: W. ELLIS HALL, Atlantic Refining Company, Midland, Texas
First Vice-President: RICHARD D. JONS, c/o Ralph Lowe, Midland, Texas
Second Vice-President: LEO HENDRICKS, Texas Christian University, Fort Worth, Texas
Secretary: KENNETH R. ETTER, Phillips Petroleum Company, Midland, Texas
Treasurer: DAVID S. HOLLAND, Ohio Oil Company, Midland, Texas
Past-President: GARNER L. WILDE, Humble Oil & Refining Company, Midland, Texas

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